COMPARING PLANT YIELD AND COMPOSITION WITH SOIL PROPERTIES USING CLASSICAL AND GEOSTATISTICAL TECHNIQUES

by

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Declaration

I, the undersigned, hereby declare that the work contained in this thesis is entirely my own original research, except where acknowledged, and that it has not at any time, either partly of fully, been submitted to any University for the purposes of obtaining a degree.

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ABSTRACT

Plant nutrient management plays a vital role in the success or failure of modern lucerne production. In South Africa, lucerne is produced under a wide range of climatic conditions, under dryland and irrigation and in some areas throughout the year. This means that there is a continuous demand for nutrients under a wide range of environmental conditions. The most important factors affecting the nutrient requirement of lucerne is yield, the cutting schedule, climate and management practices. To enable site-specific crop requirements, the spatial variation of soil and plant properties within a field can be managed with the use of geostatistical techniques. Some work has also been done to evaluate the use of geostatistics in the design of agricultural field experiments to provide better field characterization and improve plot layout. The aim of this study was to compare plant yield and composition with soil properties using both classical and geostatistical techniques. The study was conducted from June 2001 to February 2002 on an 18 ha lucerne stand in the Brits district in the North West Province. A rectangular area of 160 m X140 m was demarcated as the study area and comprised of two soil units (Hutton and Shortlands forms). Seventy-two sampling points (nodes) were laid out on a 20 m square grid, with an additional 90 sampling points laid out on a 2.5 m square grid at six randomly selected node points. Soil (0 – 300 mm) and plant samples were taken within a 0.6 m square at each of the sampling points for chemical analysis. Starting in June 2001, yield sampling was done on six occasions, at approximate intervals of 5 weeks. A randomized complete block design trail layout was superimposed on the geostatistical grid design and consisted of seven pseudo treatments, replicated four times. Basic statistical analyses were performed and spatial presentations of the variation of the plant and soil properties and lucerne yield were made using geostatistical analyses. Analyses of variance were used to test for differences between pseudo treatments for all plant and soil properties. The two soils on the study site, exhibited differences in certain properties, which caused a bi-modal population in the data. Poor correlations were found between plant nutrient uptake and soil properties as well as yield, with little or no resemblance when comparing their spatial distribution. This emphasizes the fact that the uptake of elements is not solely dependant on the concentrations thereof in the soil solution, but on other factors. Temporal variations in lucerne yield were also observed. Although there were large differences in spatial variation of lucerne yields across harvesting events, similar spatial patterns were evident. From an analysis of variance of the RCB design it was concluded that the experimental field was homogeneous enough to lay out a standard block design experiment. However, scrutiny of the structure of spatial variability of pH(H_2O) revealed that the standard RCB designs did not provide homogeneous blocks with respect to soil variability. The consequent redesign of the experiment whereby all plots were randomly allocated to treatments and replications, led to dramatically different results: significant differences were obtained for plant and soil properties as a function of the pseudo treatments. From this study it is clear that spatial variability of soil and plant properties can jeopardize the results of a standard block design field experiment and it is therefore recommended that the layout of field experiments should be designed to the cognizance of the spatial variation of a soil property that correlated highly with a chosen response variate.

CHAPTER 1

INTRODUCTION

Plant nutrient management plays a vital role in the success or failure of modern lucerne (*Medicago sativa* L.) production. In South Africa, lucerne is produced under a wide range of climatic conditions, under dryland and irrigation. In the warmer regions, lucerne is produced throughout the year, which means that there is a continuous demand for nutrients under a wide range of environmental conditions. According to Fick, Holt and Lugg (1988), the lucerne crop usually shows a response to wide variety of environmental conditions, which also depends on factors such as the age, growth stage, prior condition and genotype of the crop.

There are several factors affecting the nutrient requirements of lucerne of which yield, cutting schedule, climate and management are the most important (Lanyon & Griffith, 1988). Studies show that there is a substantial increase in yield in response to nutrient applications and therefore nutrient requirement increase with increased yields.

Rhykerd and Overdahl (1972), found that the production of high-yielding lucerne removes much larger amounts of nutrients from the soil than grain crops such as maize or wheat. Thus, to obtain high yield levels, soil fertility status and plant nutrient concentrations must be monitored and adjusted to assure adequate nutrient availability. Lucerne has a high requirement for nutrient elements such as nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg) and sulphur (S). Essential micronutrient elements are, *inter alia* boron (B) and molybdenum (Mo). Of these elements N is obtained by symbiosis with certain N fixing bacteria, if conditions are ideal, and do not have to be supplemented.

The second factor that influence nutrient uptake is the cutting schedule. A close relationship exists between lucerne maturity and nutrient concentration. Lucerne is harvested at vegetative to early reproductive growth stages in high-yielding systems. When lucerne is harvested at a less mature growth stage, such as full bud rather than 10% blossom, the leaf-stem ratio is higher with a consistent increase in the concentration of P, K, Ca and Mg in the dry material.

A third factor that influences the nutrient uptake of lucerne is climate. Temperature, light intensity, rainfall patterns and day-length change within and among the harvest intervals of the production year. The variation in environmental conditions will influence nutrient concentrations in forage, because of changes in rate of dry matter production, ion movement in the soil, root activity and the uptake of nutrients by the plant.

The fourth factor that influences the nutrient uptake of lucerne is the management practices. Successful lucerne stands are obtained on deep, well-drained soils with $pH(H_2O)$ = 6.2 – 7.8, P(Bray 1) $\geq$ 25 $mg.kg^{-1}$, K $\geq$ 80 $mg.kg^{-1}$, Ca $\geq$ 600 $mg.kg^{-1}$ and Mg $\geq$ 600 $mg.kg^{-1}$ (Fertilizer Society of South Africa, 1991).

Fertilizer recommendations will therefore depend on factors such as yield, cutting schedule and the soil nutrient status. The precision of statements that can be made about soil properties at any location depends largely on the amount of variation within the area sampled. Spatial and temporal variation of soil properties causes uncertainty in agricultural decision-making, but this variation is manageable if it is significant, controllable and predictable (Cook & Bramley, 2000). Traditionally, spatial variation is managed by grouping properties together in seemingly homogeneous units and assuming variability within the units to be purely random or uncorrelated. It also assumes that the sample mean is the best estimate of a soil property at any location within the sampling areas. The precision of these properties is characterized by parameters such as variance, standard error and confidence limits. The classical approach, however, takes no account of spatial correlation and the relative positions of sampling points. This results in the field being managed uniformly for activities such as sowing and fertilizer application, ignoring the soil spatial variability and hence the site-specific crop requirement (McBratney & Pringle, 1997). Site-specific management, unfortunately, requires a large investment in collecting the data required to make informed decisions at this scale, and prohibits the adoption of such an intensive management programme. Today, however, the spatial variation within a field can be managed with the use of geostatistical techniques. Soil scientists are restricted to limited observations, necessitating interpolation to estimate values at unsampled locations. The precision of such interpolations is strongly influenced by the variability of soil both within sampling units and between locations (Trangmar, Yost & Uehara, 1985).

Conceptually, geostatistics offers an alternative approach in that spatial correlations are quantified, and estimates for a property at an unsampled location principally determined by measurements made close by, rather that assuming a class or plot average (Warrick, Myers & Nielsen, 1986; Di, Trangmar & Kemp, 1989) and thus, managing the spatial variation within a field to ensure cost effective management practices and the optimal use of resources. Based on the premise that the spatial variability of crop yield is influenced by spatial variability in soil factors at a similar scale, researchers have begun to examine the patterns observed in crop yield maps to identify potential management zones within a field as well as to improve sampling scheme designs (Stafford, Ambler, Lark & Catt, 1996; Venter, Beukes, Claassens & Van Meirvenne, 2003a; Frogbrook, Oliver, Salahi & Ellis, 2002). According to Boydell and McBratney (2002), stable yield zone patterns can be identified by using multi-seasonal yield maps.

Historically, the methodology for geostatistics began in mining engineering for assessment of ore bodies in South Africa by D. G. Krige, after whom "kriging" is named. The earlier development of techniques was for the application of very practical problems, for example to optimize the selection of blocks of ore to be processed on a sliding economic scale according to market price of the end product. Some of the terminology that is still in use originated from the South African gold mining industry like sill, range and nugget. The latter refers to the analogy where a pure gold nugget exists and at any finite distance away a much lower concentration is found. Dimensionally, applications of geostatistics could be for distances of a few molecules or kilometers.

A review of applications of geostatistics in soil science has been given by Warrick *et al.* (1986) and covers a number of soil properties like soil pH, organic C, electrical conductivity, sand content, water retention and soil temperature. Another application of geostatistics is in precision agriculture where the aim is to match "resource application and agronomic practices with soil attributes and crop requirements as they vary across a site". In their paper, McBratney & Pringle

(1997) discuss geostatistical methods to assess spatial variation of soil with reference to the implications for precision agriculture.

Some work has been done to evaluate the use of geostatistics in the design of agricultural field experiments (Dulaney *et al.,* 1994; Van Es *et al.,* 1989; Fagroud & Van Meirvenne, 2002). Dulaney *et al.* (1994), stated that geostatistical techniques have the potential to provide better field characterization, improve plot layout, increase the power of the consequential statistical techniques and can be used to select an optimal sampling strategy for characterization of soil spatial variability at the experimental field site. This is relevant because the costs associated with conducting long-term agricultural experiments make it imperative to obtain at least some level of assurance that the data used to establish field trials are precise enough for its intended purpose.

Agricultural researchers have long understood that the effect of locality, which is often caused by natural soil variability, or previous land-use practices, can significantly reduce the ability to detect experimental treatment differences (Dulaney, Lengnick & Hart, 1994). Present-day agronomic research has reached a point where the treatment effects being tested are small and the degree of accuracy required in such studies cannot easily be obtained with conventional experimental designs (Van Es, Van Es & Cassel, 1989). It is therefore imperative to establish a high level of experimental precision.

The adverse effects stemming from soil heterogeneity can be addressed by (1) conducting the study on uniform land, or (2) controlling the effects of soil variability through experimental design and improved statistical analysis in order to better account for the effect of field variability on experimental results (Van Es *et al.*, 1989). The latter measure includes replication, blocking, randomization, row-and-column designs and methods such as nearest neighbour and trend analysis. In general, such methods improve the detection of treatment effects, although improper block layout may actually adversely affect the analysis of experiments (Van Es & Van Es, 1993). In the presence of a significant spatial correlation over small distances, the assumption of independence between plots is violated and the researcher may be faced with contradictory results. The latter can result in clear differences in crop yields between experimental plots but no significant treatment effect (Fagroud & Van Meirvenne, 2002).

The objectives of this study were to:

- Examine the effects of spatial variation of certain soil properties on the winter yield of a lucerne stand.
- Explore the spatial relations between nutrient uptake of lucerne and soil properties.
- Investigate the temporal and spatial relations of nutrient uptake and yield of lucerne.
- Examine the spatial variation of soil and plant properties and its effects on the statistical design of a field experiment.

CHAPTER 2

THE EFFECTS OF SPATIAL VARIATION OF CERTAIN SOIL PROPERTIES ON THE WINTER YIELD OF A LUCERNE STAND

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2.1 Abstract

In general, agricultural fields are managed as uniform units, ignoring spatial soil heterogeneity and its effects on growth and yield of field crops. This study was conducted from June 2001 – February 2002 and examines the effects of spatial variation of soil properties on the winter yield of a two-year-old lucerne stand on two soil types using geostatistical procedures. Seventy-two sampling points (nodes) were laid out on a 20 m square grid, with an additional 90 sampling points laid out on a 2.5 m square grid at six randomly selected node points to ensure that the total spatial structure would be identified. From initial soil sampling and analyses, the two experimental soils were classified as belonging to the Stella and Pyramid soil families with *inter alia* mean clay contents of 45% and 46%, pH(H_2O) values of 7.8 and 8.8, and mean P status (Ambic) contents of 18.3 and 6.4 mg kg^{-1}, respectively. Green biomass lucerne yield was determined on six occasions at all nodes, while soil sampling (0 - 300 mm layer) and analyses were done once in June 2001. Basic statistical analyses showed, for some soil properties, two distinct data populations, emphasizing the presence of two soil types. A yield prediction model ($R^2 = 0.55$) contained pH(H_2O), organic C, K and sand contents as variables. The geostatistical analyses of the yield model variables produced standard semi-variograms although with highly variable autocorrelation lengths. Making use of various kriging techniques, maps of soil properties and yield were compiled. These maps reveal that spatial variation of yield bears a fair resemblance to that of some soil properties and, therefore, supports the validity of the yield

prediction model. This study has shown that the scale of variation of lucerne yield can be related to that of soil properties, a finding which can be useful when designing sampling schemes.

2.2 Introduction

Plant nutrient management plays a vital role in the success or failure of modern lucerne (*Medicago sativa* L.) production. The production of high-yielding lucerne removes much larger amounts of nutrients from the soil than grain crops such as maize or wheat (Rhykerd & Overdahl, 1972). Lucerne has a high requirement for nutrient elements such as nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg) and sulphur (S). Essential micronutrient elements are, *inter alia* boron (B) and molybdenum (Mo). Apart from desirable management practices, successful lucerne stands are obtained on deep, well-drained soils with pH(H_2O) = 6.2 - 7.8, P(Bray1) $\geq$ 25 mg kg^{-1} (P(Ambic) equivalent = 21 mg kg^{-1}), K $\geq$ 80 mg kg^{-1}, Ca $\geq$ 600 mg kg^{-1} and Mg $\geq$ 600 mg kg^{-1} (Fertilizer Society of South Africa, 1991). In South Africa, lucerne is produced under a wide range of conditions, according to the area of production. In the warmer regions, lucerne is produced throughout the year, which means that there is a continuous demand for nutrients under a wide range of environmental conditions.

Sensible fertilizer recommendations depend on factors such as yield level, cutting schedule and a thorough knowledge of the soil nutrient status. The precision of statements that can be made about soil properties at any location depends largely on the amount of variation within the area sampled. Soil scientists are restricted to limited observations, necessitating interpolation to estimate values at unsampled locations. The precision of such interpolations is strongly influenced by the variability of soil both within sampling units and between locations (Trangmar, Yost & Uehara, 1985). Traditionally, spatial variation and correlation of soil parameters were managed by grouping soils together in seemingly homogeneous units and assuming variability within the units to be purely random or spatially uncorrelated. That resulted in the field being managed by uniform practices such as sowing, fertilizer and pesticide applications and ignored the spatial variability of the soil and hence the site-specific crop requirements (McBratney & Pringle, 1997). Conceptually, geostatistics offers an alternative approach in that spatial correlations are quantified, and estimates for a property at an unsampled location principally determined by measurements made close by, rather than assuming a class or plot average (Warrick, Myers & Nielsen, 1986; Di, Trangmar & Kemp, 1989). The aim of this study was to quantify the variation and spatial correlations of selected soil properties that govern the yield of a lucerne stand and to predict yield using these soil properties.

2.3 Materials and Methods

2.3.1 Field and analytical methods

The study was conducted from June 2001 to February 2002 on an 18 ha lucerne stand in the Brits district in the North West Province of South Africa (27°49'47''E, 25°33'12''S). The area has a mean annual rainfall of 650 mm and the geology consists of ferrogabro and diorite of the Rustenburg Layered Suite. A rectangular area of 160 m X 140 m was demarcated as the study area. The latter comprised two soil units, which were classified (on the basis of a field survey) as a deep (1100 mm) Hutton form (Stella family) in the southwesterly corner and a deep (1000 mm) Shortlands form (Pyramid family) (Soil Classification Working Group, 1991) towards the northeasterly part of the field (Table 2.1) and covers approximately 80 % of the total area. The clay mineralogy of the two soil units was determined using the X-ray diffraction method. The lucerne stand was 2 years old when the trial commenced, and had been irrigated by a sprinkler irrigation system.

Seventy-two sampling points (nodes) were laid out on a 20 m square grid, with an additional 90 sampling points laid out on a 2.5 m square grid at six randomly selected node points to ensure that the total spatial structure would be identified. All sampling points were georeferenced using a Global Positioning System (GPS) and marked with flat metal discs. Figure 2.1 shows an aerial photograph of the field with the sampling points described as small black dots.

Table 2.1 Characteristics of the two experimental soils

Soil Family	**Stella**		**Pyramid**		
Horizons	A1	B1	A1	B2	B3
Depth (mm)	0 – 300	300 – 1000	0 – 250	250 – 550	550 – 1100
Properties					
$pH(H_2O)$	7.67	8.05	8.44	8.66	9.32
Org. C (%)	1.25	1.12	-	-	-
P ($mg\ kg^{-1}$)	18.53	3.15	4.51	-	-
Ca ($mg\ kg^{-1}$)	1618	3550	4326	4152	3068
K ($mg\ kg^{-1}$)	78.2	70.4	160.3	109.5	93.8
Na ($mg\ kg^{-1}$)	18.4	32.2	55.2	181.7	110.4
Mg ($mg\ kg^{-1}$)	566	784	1270	2359	1914
Elec. cond. ($mS\ m^{-1}$)	33	66	45	70	103
Clay (%)	42.0	48.8	45.9	54.3	37.7
Silt (%)	13.7	15.6	19.0	17.5	19.2
Sand (%)	42.3	33.4	33.7	25.7	41.4
Dominant clay mineral	Kaolinite	-	Smectite	-	-

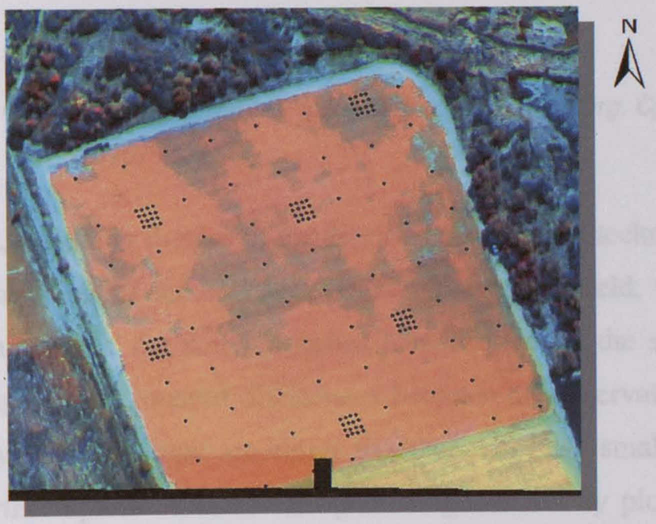


Figure 2.1 An aerial photograph of the field. The black dots depict the sampling points.

Harvesting was done by cutting and weighing the above ground plant parts within a 0.6 m square around each of the sampling points to determine green biomass yield. Starting in June 2001, yield sampling was done on six occasions, at approximate intervals of 5 weeks. At each of the sampling points three soil samples were taken in June 2001 within the 0.6 m square from the 0 – 300 mm soil layer and thoroughly mixed to serve as a composite sample. These samples were analyzed for K, Ca, Mg, sodium (Na) (ammonium acetate), P(Ambic) and organic C content, as well as for pH(H_2O), electrical resistance, particle size (hydrometer – 3 fractions) and water retention (at -33kPa) using the standard methods described in the Handbook of Standard Soil Testing Methods for Advisory Purposes (Non-Affiliated Soil Analysis Work Committee, 1990).

2.3.2 *Statistical methods*

For the purpose of this study only yield and soil data from the June 2001 sampling were analyzed. Basic analyses (Hintze, 1997) to obtain information on the frequency distribution, standard deviation and coefficients of variation were performed on all soil properties and lucerne yields (Table 2.2). An all-possible regression analysis (step-wise regression) was performed to identify the primary soil properties that govern the yield of the field. A model for the prediction of the yield from the soil properties was generated using a multiple linear regression analysis and is described by:

$$\text{Green biomass yield} = 512.7591 - 62.29047*(pH(H_2O)) + 202.8696*(Org.\ C) - 0.259602*(K) + 1.038987*(Sand) \qquad (R^2 = 0.55) \qquad (2.1)$$

Geostatistical analyses, including the use of the kriging interpolation technique to generate spatial presentations of the variation of the soil properties and lucerne yield, were performed (Hunt, 2002). The spatial structure of the soil properties is described by the semi-variance, which is estimated as the average of the squared differences between all observations separated by a lag distance. Consequently the points that are closer together will have smaller semi-variances than the points that are further apart. A semi-variogram is generated by plotting the semi-variance against the lag and is modeled by a mathematical function. Kriging interpolation is then used to estimate values at unsampled locations, which can be mapped (Webster & Oliver, 2000). In those cases where data populations were normally distributed, standard semi-variograms and ordinary kriging were used for estimation purposes. For bi-modal data populations the indicator kriging method was used (Goovaerts, 1997; Hunt, 2002). All estimates were contoured and mapped (Golden Software Inc., 1995) to illustrate the spatial variability of properties.

Table 2.2 Statistical descriptions of topsoil properties and yield.

	Minimum	Maximum	Mean	Median	Std. dev.	CV
pH(H_2O)	7.5	9.0	8.3	8.4	0.4	0.05
Org. C (%)	0.88	1.48	1.15	1.14	0.14	0.12
P (mg kg^{-1})	5.1	65.19	19.35	16.58	9.91	0.51
Ca (mg kg^{-1})	1565	8657	4798	5140	1570	0.33
K (mg kg^{-1})	94	468	222	221	65	0.30
Na (mg kg^{-1})	56	531	172	127	117	0.68
Mg (mg kg^{-1})	399	1917	1116	945	451	0.40
Resistance (ohm)	340	1800	699	440	488	0.70
Clay (%)	38.0	50.0	42.9	42.0	2.8	0.07
Silt (%)	12.1	35.5	22.4	21.9	4.0	0.18
Sand (%)	21.1	47.2	34.7	34.9	5.4	0.16
Water reten. (%) (at -33kPa)	16.4	37.5	27.3	26.9	3.9	0.14
Yield (t ha)	1.6	10.7	5.7	5.4	2.0	0.36

2.4 Results and Discussion

2.4.1 *Soil characteristics*

The two experimental soils have apedal (Stella) and blocky structured (Pyramid) B-horizons. Dominant clay minerals in the A horizon are kaolinite (approximately 80 %) and smectite (approximately 70 %), respectively. Both soils are deep (1000 – 1100 mm) and have high topsoil clay contents (43 – 54 % clay) with a clay texture. Soil chemical properties like pH(H_2O), Ca and Mg are markedly different between the two soils. Soil pH(H_2O) (too high) and P status (too low) (FSSA, 1991) are not conducive to optimal lucerne growth (Table 2.1), rendering P fertilization necessary.

2.4.2 Statistical analyses

Since the semi-variogram is based on variances, the statistical distribution of the data should ideally be close to normal to ensure that the variances are stable. However, the preliminary analyses indicated that most of the soil properties had a skew distribution (data not included) and had to be transformed. The histograms of pH(H_2O), Mg, Ca and resistance indicated that there are two distinct, relatively normally distributed populations of data. The latter is probably a result of the two soil types present in the experimental area. The histograms of the P status and exchangeable Na of the soil and that of lucerne yield were positively skewed. Several transformations (logarithmic, $\log_e$ and square-root) were performed to obtain symmetrical distributions and the best transformation for each soil property was selected. The correlation coefficients of the soil and plant properties were computed and are presented in Table 2.3.

Table 2.3 A correlation matrix for soil properties and lucerne yield.

	pH(H_2O)	C	P	Ca	K	Mg	Elec. res.	Sand	Measured Yield
pH(H_2O)	1								
C	-0.63	1							
P	-0.52	0.30	1						
Ca	0.77	-0.28	-0.57	1					
K	0.38	0.19	0.00	0.57	1				
Mg	0.78	-0.54	-0.50	0.83	0.40	1			
Elec. res.	-0.70	0.26	0.46	-0.65	-0.41	-0.56	1		
Sand	-0.32	-0.22	0.52	-0.53	-0.36	-0.30	0.41	1	
Measured Yield	-0.70	0.55	0.34	-0.57	-0.31	-0.62	0.43	0.18	1

The yield prediction model contained the variables pH(H_2O), organic C, K and sand content. In a similar study, Frogbrook, Oliver, Salahi and Ellis (2002) found that soil pH, P and K, amongst others, determined the spatial yield of a cereal crop. Although phosphorus is essential to lucerne plants in its involvement in adenosine triphosphate (ATP) associated with nitrogenase activity, the correlation between soil P and yield was relatively low (r = 0.34). This may be explained in that P status values were sub-optimal for good lucerne growth.

2.4.3 Spatial analyses

In this paper only those soil properties that were used in the yield prediction model are discussed (see equation 2.1). Of the four properties included in the model, only pH(H_2O) exhibited a bi-modal distribution reflecting the presence of two soil types within the experimental area. However, the southwesterly part had too few sampling points to compute a semi-variogram and indicator kriging (IK) was used to estimate this property. Indicator kriging is a non-linear, non-parametric form of kriging (Webster and Oliver, 2000) in which continuous variables are converted to binary indicators. This makes the approach suited to non-normal and crude data. The dataset was divided into nine percentile ranges (Isaaks & Srivastava, 1989) that served as the threshold values. An isotropic, indicator semi-variogram was computed for each of the percentile ranges and then used to do a multiple indicator kriging analysis.

No preferential long or short-range directions could be identified for the soil K content and thus an isotropic semi-variogram was modeled. Well-defined long and short-range an-isotropic semi-variograms were modeled for the organic C, sand content, yield and predicted yield using a double spherical model (Webster & Oliver, 2000) given by:

$$\gamma(h)=\gamma_0(h)+\gamma_1(h)+\gamma_2(h) \qquad \text{with :} \tag{2.2}$$

$$\gamma_0(h)=\begin{cases}0 & \text{if } h=0\\ C_0 & \text{if } h>0\end{cases}$$

$$\gamma_1(h)=C_1\left(\frac{3h}{2a_1}-\frac{1}{2}\left(\frac{h}{a_1}\right)^3\right) \qquad 0<h\le a_1$$

$$\gamma_1(h)=C_1 \qquad h>a_1$$

$$\gamma_2(h)=C_2\left(\frac{3h}{2a_2}-\frac{1}{2}\left(\frac{h}{a_2}\right)^3\right) \qquad h\le a_2$$

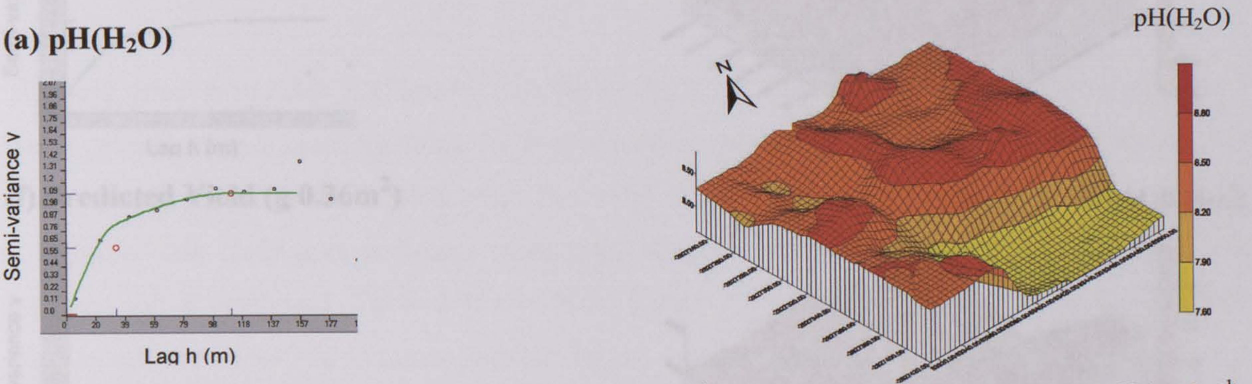
$$\gamma_2(h)=C_2 \qquad h>a_2$$

with C_0 the nugget effect, a_1 and a_2 the short and long ranges, respectively, C_1 and C_2 the sill coefficients of both structures, $C_0+C_1+C_2$ the overall sill and h the lag distance. The variograms and the maps of the kriged estimates are shown in Figure 2.2. The model parameters are given in Table 2.4. The estimation error of predicted yield was also calculated and mapped (Figure 2.3).

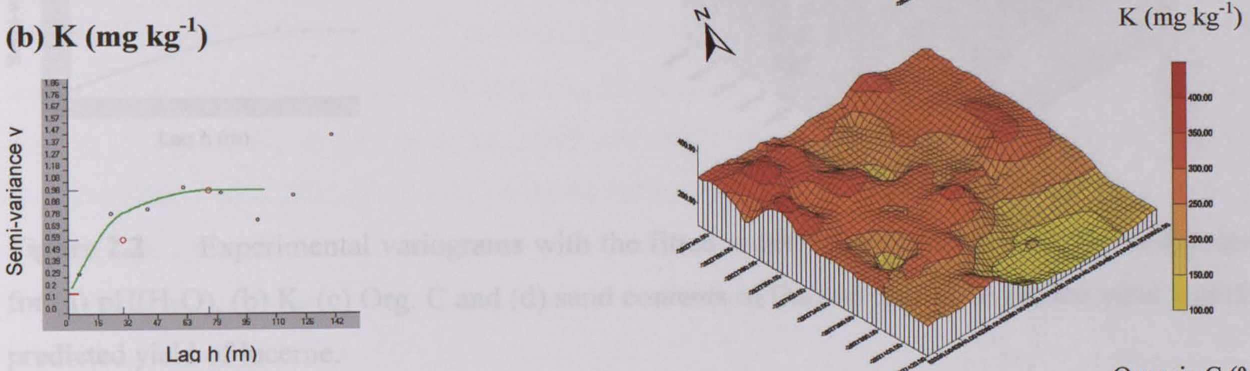
Table 2.4 Model parameters for soil properties and lucerne yield.

	Model	Nugget	Sill	Long range (m)	Short range (m)
pH(H_2O)	Spherical	0.01	0.98	112.3	-
K	Spherical	0.17	0.82	74.5	-
Org. C	Spherical	0.30	0.99	111.9	58.7
Sand	Spherical	0.21	0.78	220.0	75.4
Measured Yield	Spherical	0.24	1.17	90.1	48.1
Predicted Yield	Spherical	0.12	0.88	115.6	61.7

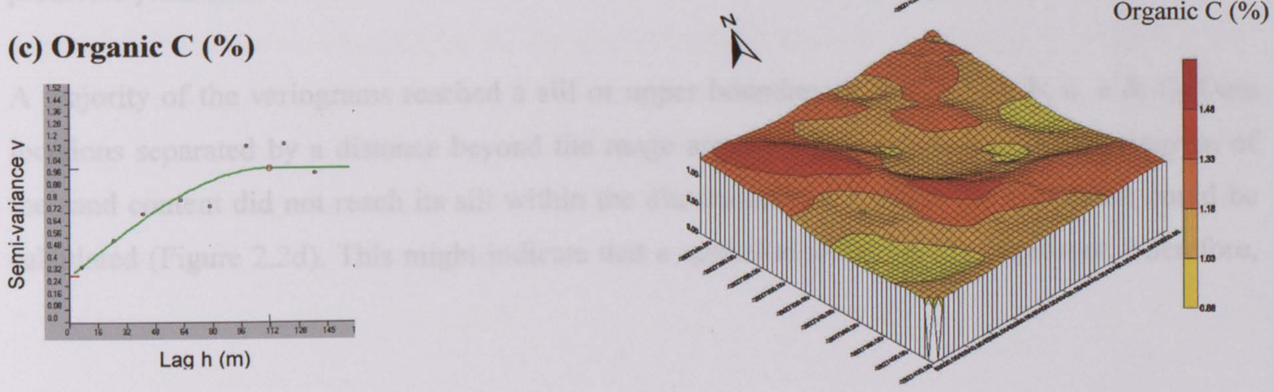
(a) pH(H_2O)



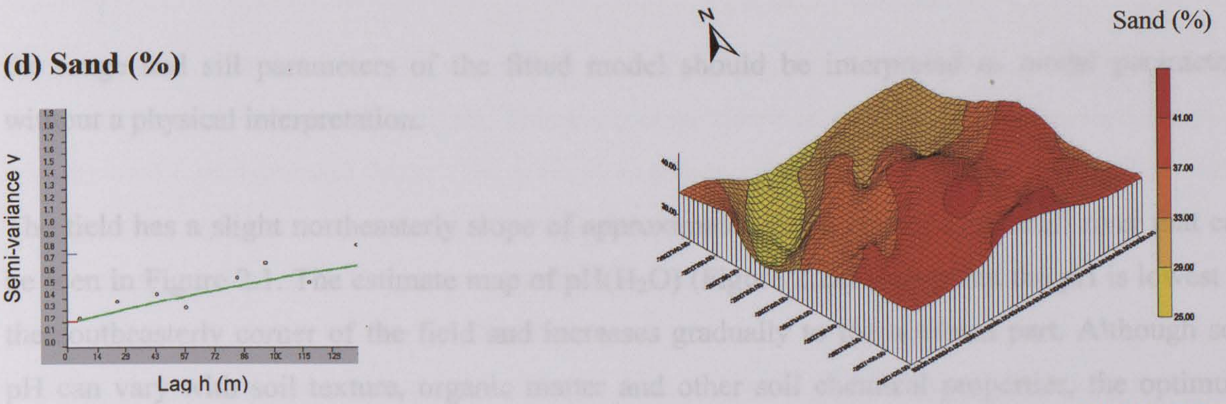
(b) K (mg kg^{-1})



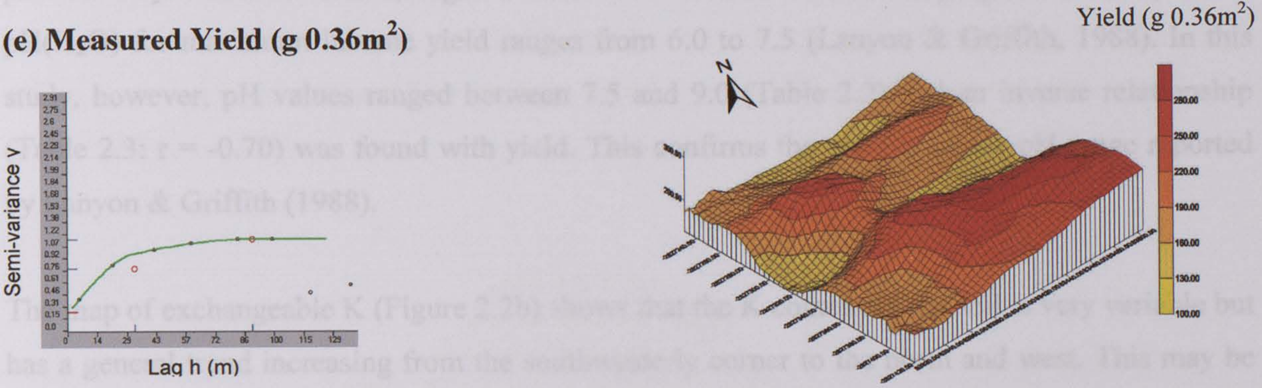
(c) Organic C (%)



(d) Sand (%)



(e) Measured Yield (g 0.36m^2)



(f) Predicted Yield (g 0.36m^2)

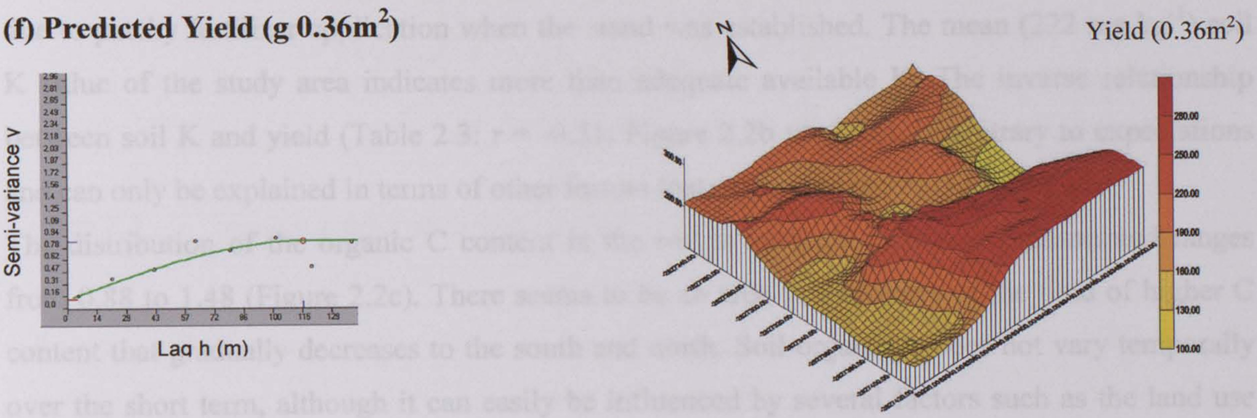


Figure 2.2 Experimental variograms with the fitted models and maps of the kriged estimates for (a) pH(H_2O), (b) K, (c) Org. C and (d) sand contents of the soil as well as (e) the yield and (f) predicted yield of lucerne.

A majority of the variograms reached a sill or upper boundary (Figures 2.2a, b, c, e & f). Data locations separated by a distance beyond the range are spatially independent. The variogram of the sand content did not reach its sill within the dimensions over which the variogram could be calculated (Figure 2.2d). This might indicate that a spatial non-stationarity is present. Therefore, the range and sill parameters of the fitted model should be interpreted as model parameters without a physical interpretation.

The field has a slight northeasterly slope of approximately 2 %, ending in a small river that can be seen in Figure 2.1. The estimate map of pH(H_2O) (Figure 2.2a) shows that the pH is lowest in the southeasterly corner of the field and increases gradually to the northern part. Although soil pH can vary with soil texture, organic matter and other soil chemical properties, the optimum pH(H_2O) for maximum lucerne yield ranges from 6.0 to 7.5 (Lanyon & Griffith, 1988). In this study, however, pH values ranged between 7.5 and 9.0 (Table 2.2) and an inverse relationship (Table 2.3: $r = -0.70$) was found with yield. This confirms the validity of the pH range reported by Lanyon & Griffith (1988).

The map of exchangeable K (Figure 2.2b) shows that the K content of the soil is very variable but has a general trend increasing from the southwesterly corner to the north and west. This may be due to patchy fertilizer application when the stand was established. The mean (222 mg kg^{-1}) soil K value of the study area indicates more than adequate available K. The inverse relationship between soil K and yield (Table 2.3: $r = -0.31$; Figure 2.2b vs. 2.2e), is contrary to expectations and can only be explained in terms of other factors that may determine yield response.

The distribution of the organic C content in the soil is spatially relatively uniform and ranges from 0.88 to 1.48 (Figure 2.2c). There seems to be an area in the centre of the field of higher C content that gradually decreases to the south and north. Soil organic C does not vary temporally over the short term, although it can easily be influenced by several factors such as the land use and management practices. It is, however, positively correlated with the lucerne yield (Table 2.3: $r = 0.55$), and is associated with higher nutrient concentrations.

Figure 2.2d shows the estimate map of the sand content of the soil. Sand content increases from the northwesterly corner across the field to the eastern corner. Sand content is an inherent soil property and cannot be manipulated by management practices. Sand content does not have a bounded semi-variogram, which means that the full extent of the spatial variation has not been encompassed at this scale of sampling. It also has a very weak correlation with yield (Table 2.3: $r = 0.18$).

The measured green biomass yield map (Figure 2.2e) shows that the values were generally larger in the southeastern corner of the field. There is a clear visual resemblance between biomass yield and the best correlated soil properties, soil pH and organic C. Although the nugget of the semi-variogram is less and the correlation range longer than that of measured yield, the map of predicted yield (Figure 2.2f) shows a good resemblance. This indicates that the green biomass yield of lucerne could be fairly accurately predicted from soil properties such as pH(H_2O), organic C, exchangeable K and sand content. The predicted yield map (Figure 2.3) showed a mean error of 21.2 %. The latter could possibly be minimized with the use of normalized differential vegetation index (NDVI) values and the inclusion of soil water features such as the water-holding capacity.

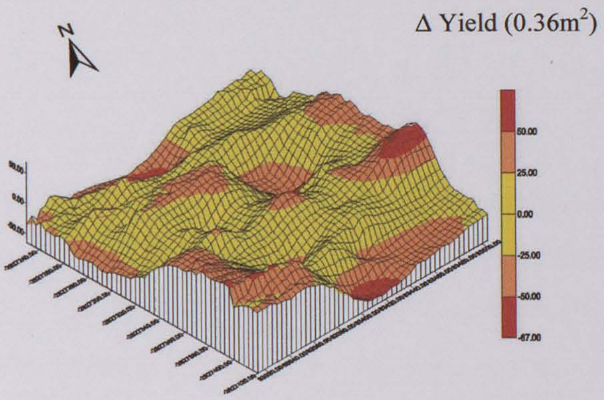


Figure 2.3 Estimation error map of predicted yield.

2.5 Conclusions

The two soils of the study site, although similar in certain aspects, exhibited differences in pH(H_2O), Ca, Mg and dominant clay minerals. These differences caused distinct bi-modal populations of data when subjected to statistical analysis. The majority of properties showed considerable variation and highly variable autocorrelation lengths. Simple linear regression analyses showed that the soil properties pH(H_2O), organic C, exchangeable Ca and Mg contents are individually well correlated with green biomass lucerne yield. A prediction model for lucerne yield (R^2 = 0.55) was obtained from stepwise multiple regression analyses. The model had pH(H_2O), organic C, exchangeable K and sand contents as variables. Although soil P status is a major nutrient element for lucerne growth, it did not feature in the prediction model. The geostatistical procedures allowed the construction of maps to demonstrate the spatial variability of soil properties and of lucerne yield. The fair resemblance between the measure and predicted yield maps supports the validity of the yield prediction model. The conclusion of Frogbrook *et al.* (2002) that the scale of variation of the yield can be related to that of soil properties is supported by this study. This can be useful in designing an appropriate sampling scheme for observing soil properties in future.

CHAPTER 3

EXPLORING THE SPATIAL RELATIONS BETWEEN PLANT ELEMENT UPTAKE OF A LUCERNE STAND AND SOIL PROPERTIES

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3.1 Abstract

There are several factors affecting the nutrient requirements of lucerne (*Medicago sativa* L.) of which yield level, cutting schedule, climate and management practices are the most important. Successful lucerne stands are obtained on deep, well-drained soils with pH(H_2O) = 6.2 - 7.8, P(Bray1) $\geq$ 25 mg kg^{-1}, K $\geq$ 80 mg kg^{-1}, Ca $\geq$ 600 mg kg^{-1} and Mg $\geq$ 600 mg kg^{-1}. This study was designed to quantify the spatial variability of the soil and plant properties and, consequently, to explore the spatial relations between plant element uptake and soil properties using geostatistical procedures. Seventy-two sampling points (nodes) were laid out on a 20 m square grid, with an additional 90 sampling points laid out on a 2.5 m square grid at six randomly selected node points to ensure that the total spatial structure would be identified. Plant and soil samples (0 – 300 mm layer) were collected in June 2001 and analyzed for several plant and soil properties. Linear regression analyses, in general, showed poor correlation between plant element uptake and soil properties. Geostatistical analyses of plant and soil variables produced considerable variation and highly variable autocorrelation lengths. When comparing spatial maps of plant Ca, Mg and P contents with their soil counterparts, no resemblance could be found, while for K some spatial agreement between plant and soil values was noticeable. Making use of a multiple regression equation, very good agreement was found between the spatial distribution of measured and predicted plant K. This emphasizes the fact that the uptake of elements by plants is not solely dependent on the concentrations thereof in the soil solution, but on other factors as well.

3.2 Introduction

There are several factors affecting the nutrient requirements of lucerne (*Medicago sativa* L.) of which yield level, cutting schedule, climate and management are the most important (Lanyon & Griffith, 1988). Studies show that there is a substantial increase in yield in response to nutrient applications and that the uptake of all nutrients increases as yield increases. According to Rhykerd and Overdahl (1972), the production of high-yielding lucerne removes much larger amounts of nutrients from the soil than grain crops such as maize or wheat. Thus to obtain high yield levels, soil fertility status and plant nutrient concentrations must be monitored and adjusted to ensure adequate nutrient availability.

The second factor that influences nutrient uptake of lucerne is the cutting schedule. A close relationship exists between lucerne maturity and nutrient concentration. Lucerne is harvested at vegetative to early reproductive growth stages in high-yielding systems. When lucerne is harvested at a less mature growth stage, such as full bud rather than 10% blossom, the leaf-stem ratio is greater with a consistent increase in the concentrations of P, K, Ca and Mg in the herbage. A third factor that influences the nutrient uptake of lucerne is climate. In South Africa, lucerne is produced under a wide range of conditions. In the warmer regions, lucerne is produced throughout the year, which means that there is a continuous demand for nutrients under a range of environmental conditions. Temperature, light intensity, rainfall patterns and day-length change within and between the harvest intervals of the production year. The variation in environmental conditions will influence nutrient concentrations in forage because of changes in the rate of dry matter production, ion movement in the soil, root activity and the uptake of nutrients by the plant. The fourth factor that influences the nutrient uptake of lucerne is the management practices. Successful lucerne stands are obtained on deep, well-drained soils with pH(H_2O) = 6.2 - 7.8, P(Bray1) $\geq$ 25 mg kg^{-1}, K $\geq$ 80 mg kg^{-1}, Ca $\geq$ 600 mg kg^{-1} and Mg $\geq$ 600 mg kg^{-1} (Fertilizer Society of South Africa, 1991). Traditionally, spatial variation of soil parameters is managed by grouping soils together in seemingly homogeneous units and assuming variability within the units to be purely random or spatially uncorrelated. This approach results in the field being managed by uniform practices such as sowing, fertilizer and pesticide applications and ignoring the spatial variability of the soil and hence the site-specific crop requirements (McBratney & Pringle, 1997).

Today, however, the spatial variation within a field can be managed with the use of geostatistical techniques to ensure cost effective management practices and the optimal use of resources. The aims of this study were to quantify the spatial variability of selected soil and plant properties and, consequently, to explore the spatial relations between plant element uptake and soil properties.

3.3 Materials and Methods

3.3.1 *Field and analytical methods*

The study was conducted from June 2001 to February 2002 on an 18 ha lucerne stand in the Brits district in the North West Province of South Africa (27°49'E, 25°33'S). The area has a mean annual rainfall of 650 mm and the geology consists of ferrogabro and -diorite with bands and bodies of magnetite. A rectangular area of 160 m X 140 m was demarcated as the study area. The latter consisted of two soil mapping units, which were classified as a deep (1100 mm) Hutton form (Stella family) in the southwesterly corner and a deep (1000mm) Shortlands form (Pyramid family) towards the northeasterly part of the field (Venter,Beukes, Claassens & Van Meirvenne, 2003). The lucerne stand was 2 years old when the trial commenced, and had been irrigated by a sprinkler irrigation system. At the establishment of the stand, 500 kg ha^{-1} superphosphate and 200 kg ha^{-1} potassium chloride were applied as fertilizer. Seventy two-sampling points (nodes) were laid out on a 20 m square grid, with an additional 90 points on a 2.5 m square grid at six randomly selected node points to ensure that the total spatial structure would be identified. Figure 3.1 shows an aerial photograph of the field with the sampling points depicted as small black dots.

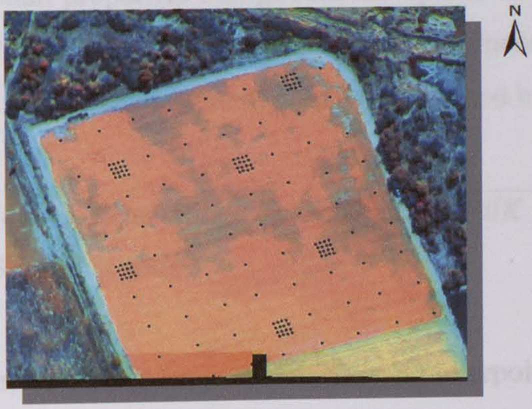

Figure 3.1 An aerial photograph of the field. The black dots depict the sampling points.

Starting in June 2001, yield sampling was done on six occasions, at approximate intervals of 5 weeks. The plant samples of the June 2001 harvest were analyzed for potassium (K), calcium (Ca), magnesium (Mg) and phosphate (P) content using standard methods (Agri Laboratory Association of Southern Africa, 1998). Soil samples taken at the sampling points were analyzed for K, Ca, Mg, sodium (Na), P and organic C content, as well as for pH(H_2O), electrical resistance, texture and water retention (at -33kPa) using standard methods (Non-Affiliated Soil Analysis Work Committee, 1990). Details of the experimental layout, sampling and analytical procedures are reported elsewhere (Venter *et al.*, 2003). Soil and plant analysis results are given in Table 3.1. The plants were cut at an early flowering stage and analyses were performed on the whole plant.

3.3.2 *Statistical methods*

Basic statistical analyses (Hintze, 1997) were performed to obtain information on the frequency distribution, standard deviation and coefficients of variation on all soil and plant properties (Venter *et al.*, 2003). These preliminary analyses indicated that most of the soil properties had a positively skewed distribution, and several transformations (logarithmic, $\log_e$ and square-root) were performed prior to subsequent analyses. All plant properties displayed a normal distribution and no transformations were conducted. Table 3.2 shows the linear correlations of some of the soil and plant properties.

An all-possible regression (step-wise regression) was performed, using the point data, to identify the primary soil and plant properties that govern the uptake of each plant nutrient, and was used to generate a dataset for geostatistical analyses. For the purpose of this paper only the model for the prediction of plant K will be discussed, which is described by:

$$PedictedPlantK = 1.745 - 5.339e^{-5}(SoilCa) + 9.659e^{-2}\left(\sqrt{SoilK}\right) + 1.829e^{-3}(Silt) + \tag{3.1}$$

$$3.367e^{-1}(PlantCa) - 3.693(PlantMg)$$

($R^2 = 0.58$)

Geostatistical analyses, including the use of the kriging interpolation technique to generate spatial presentations of the variation in the soil and plant properties, were performed (Hunt, 2002). The spatial structure of these properties is described by the semi-variance, which is estimated as the average of the squared differences between all observations separated by a lag distance. Consequently the points that are closer together will have smaller semi-variances than the points that are further apart. A semi-variogram is generated by plotting the semi-variance against the lag and is modelled by a mathematical function. Kriging interpolation is then used to estimate values at unsampled locations, which can be mapped (Webster & Oliver, 2000). In those cases where data populations were normally distributed, standard semi-variograms and ordinary kriging were used for estimation purposes. For bi-modal data populations the indicator kriging method was used (Goovaerts, 1997; Hunt, 2002). All estimates were contoured and mapped (Golden Software Inc., 1995) to illustrate the spatial variability of properties.

For the purpose of this paper the spatial variability of only four elements (Ca, Mg, K and P) for both plant and soil will be discussed. Of all the elements, only the Mg content of the soil exhibited a bi-modal distribution, reflecting the presence of two soil types within the experimental area. This necessitated the use of indicator kriging (IK) to estimate this property. According to Webster and Oliver (2000), indicator kriging is a non-linear, non-parametric form of kriging in which continuous variables are converted to binary ones (indicators). This makes this approach suited to non-normal and crude data. The dataset was divided into nine percentile ranges (Isaaks & Srivastava, 1989) that served as the threshold values. An isotropic, indicator semi-variogram was computed for each of the percentile ranges and was then used to do an indicator kriging analysis. All other properties were estimated using ordinary kriging (OK). The variograms of these properties are shown in Figures 3.2 and 3.4 and the model parameters are given in Table 3.3. The maps of the kriged estimates for the measured plant and soil properties are shown in Figure 3.3, and that of predicted plant K in Figure 3.4.

3.4 Results and Discussion

3.4.1 Plant and Soil characteristics

The two experimental soils have apedal (Stella) and blocky structure (Pyramid) B-horizons. Dominant clay minerals in the A horizon are kaolinite and smectite, respectively. Both soils are deep (1000 – 1100 mm) and have high clay contents (43 – 54 % clay). Soil chemical properties like pH(H_2O), Ca and Mg are markedly different between the two soils (Venter *et al*., 2003). The observed soil pH(H_2O) (too high) and P (too low) (FSSA, 1991) are not conducive to optimal lucerne growth. However, according to the norms of Reuter and Robinson (1997), there were adequate concentrations of all nutrients in the plants (Table 3.1).

Table 3.1 Statistical descriptions of some soil and plant properties.

		Minimum	**Maximum**	**Mean**	**Median**	**Std. dev.**	**CV**
Soil	**pH(H_2O)**	7.5	9.0	8.3	8.4	0.4	0.05
	Org. C (%)	0.88	1.48	1.15	1.14	0.14	0.12
	Ca (mg kg^{-1})	1565	8657	4798	5140	1570	0.33
	Mg (mg kg^{-1})	399	1917	1116	945	451	0.40
	K (mg kg^{-1})	94	468	222	221	65	0.30
	P (mg kg^{-1})	5.10	65.19	19.35	16.55	9.91	0.51
	Clay (%)	38	50	43	42	3	0.06
	Sand (%)	21.1	47.2	34.7	34.9	5.4	0.16
	Water retention (% at -33kPa)	16.4	37.5	27.3	26.9	3.9	0.14
Plant	**Ca (%)**	0.92	1.80	1.35	1.34	0.18	0.13
	Mg (%)	0.20	0.47	0.32	0.32	0.05	0.17
	K (%)	1.30	3.49	2.22	2.28	0.39	0.18
	P (%)	0.18	0.40	0.31	0.31	0.04	0.13
	Yield (t ha^{-1})	1.6	10.7	5.7	5.4	2.0	0.36

Table 3.2 shows that the correlations between soil and plant Mg, and K are relatively high ($r = 0.49$ and $r = 0.45$, respectively) while the correlations between the Ca and P content of the plants and soil are poor ($r = -0.13$ and $r = 0.10$, respectively). The better correlations between the plant and soil Mg and K may be due to the high uptake rate of both elements through the plant membrane and a high mobility throughout the entire plant. In the soil, K and Mg ions are adsorbed by clay minerals, and thus the behaviour of K and Mg in the soil is very much dependent on the clay content and types of clay minerals present (Mengel & Kirkby, 1987). The two soil types are dominated by kaolinite and smectite clay minerals, neither of which seems to have affected the adsorption of K. Although Mg also has a high rate of uptake, it is much lower

than that of K but it is also mobile in the phloem, which means that it can be translocated from older to younger leaves or to the apex.

Table 3.2 A correlation matrix of some of the soil and plant properties.

		Plant				*Soil*								
		Ca	**Mg**	**K**	**P**	**Ca**	**Mg**	**K**	**P**	**pH**	**C**	**WR**	**Clay**	**Sand**
Plant	**Ca**	1												
	Mg	0.05	1											
	K	0.09	-0.61	1										
	P	0.38	-0.01	0.07	1									
Soil	**Ca**	-0.13	0.34	-0.09	-0.20	1								
	Mg	-0.30	0.49	-0.23	-0.20	0.83	1							
	K	-0.15	-0.08	0.45	-0.12	0.57	0.39	1						
	P	-0.08	-0.32	0.22	0.08	-0.57	-0.50	-0.01	1					
	pH	-0.24	0.33	-0.06	-0.36	0.77	0.78	0.37	-0.52	1				
	C	0.35	-0.32	0.26	0.29	-0.28	-0.54	0.20	0.30	-0.62	1			
	WR	0.14	0.18	0.05	0.03	0.72	0.57	0.51	-0.48	0.53	0.04	1		
	Clay	0.03	0.08	0.00	0.06	0.36	0.30	0.20	-0.39	0.18	0.10	0.55	1	
	Sand	-0.27	-0.09	-0.10	-0.03	-0.53	-0.30	-0.36	0.52	-0.33	-0.22	-0.77	-0.70	1

pH = pH(H_2O)

WR = water retention at –33kPa

In contrast to the foregoing uptake phenomena, the uptake rate of Ca by plants is lower and is therefore little affected by the Ca content in the root medium, provided that the Ca availability is adequate for normal plant growth (Mengel & Kirkby, 1987). The weak correlation that exists between the soil Ca content and that of the plants can be explained by the fact that part of the high Ca content of soils is precipitated and therefore not active. Phosphorus moves through the soil solution to plant roots by diffusion, which means that it is limited and can only move short distances and may thus be positionally unavailable to the plant roots. In addition to its positional unavailability, lucerne roots absorb P largely as orthophosphate ($H_2PO_4^-$) from the soil solution (Lanyon & Griffith, 1988), which is influenced by pH. In alkaline soils, where Ca phosphates dominate, soluble P is decreased by an increase in pH and may be less available to plants.

3.4.2 Spatial analyses

All of the variograms reached an upper boundary, *i.e.* a sill at a certain lag distance or range (Figure 3.2). Data locations separated by a distance beyond the range are regarded as spatially independent (Webster & Oliver, 2000).

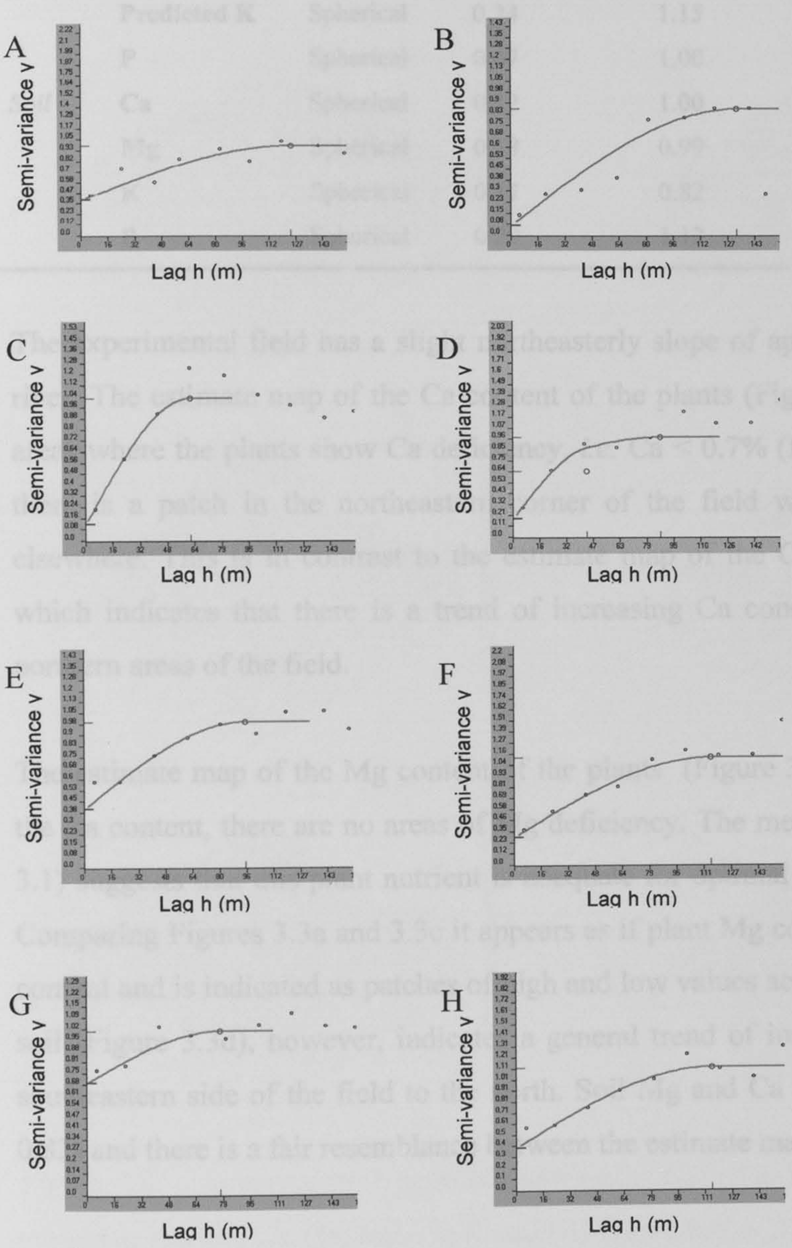

Figure 3.2 Experimental variograms with the fitted model for (A) Ca, (C) Mg, (E) K and (G) P contents of the plants and (B) Ca, (D) Mg, (F) K and (H) P contents of the soil.

Table 3.3 Model parameters for plant and soil analysis

		Model	**Nugget (c_0)**	**Sill ($c+c_0$)**	**Long range (a) (m)**	**Short range (a) (m)**
Plant	**Ca**	Spherical	0.40	1.00	125	55
	Mg	Spherical	0.13	1.04	61	-
	K	Spherical	0.41	1.00	95	59
	Predicted K	Spherical	0.24	1.15	107	56
	P	Spherical	0.67	1.00	73	-
Soil	**Ca**	Spherical	0.12	1.00	175	116
	Mg	Spherical	0.18	0.99	104	-
	K	Spherical	0.17	0.82	75	-
	P	Spherical	0.29	1.13	115	-

The experimental field has a slight northeasterly slope of approximately 2 %, ending in a small river. The estimate map of the Ca content of the plants (Figure 3.3a) indicates that there are no areas where the plants show Ca deficiency, *i.e.* Ca < 0.7% (Reuter & Robinson, 1997), although there is a patch in the northeastern corner of the field where the Ca content is lower than elsewhere. This is in contrast to the estimate map of the Ca content of the soil (Figure 3.3b), which indicates that there is a trend of increasing Ca concentration from the southern to the northern areas of the field.

The estimate map of the Mg content of the plants (Figure 3.3c) indicates that, as in the case of the Ca content, there are no areas of Mg deficiency. The mean plant Mg value of 0.32 % (Table 3.1) suggests that this plant nutrient is adequate for optimal growth (Reuter & Robinson, 1997). Comparing Figures 3.3a and 3.3c it appears as if plant Mg content is more variable than plant Ca content and is indicated as patches of high and low values across the field. The Mg content of the soil (Figure 3.3d), however, indicates a general trend of increasing Mg concentration from the southeastern side of the field to the north. Soil Mg and Ca are highly correlated (Table 3.2; r = 0.83) and there is a fair resemblance between the estimate maps of these two variables.

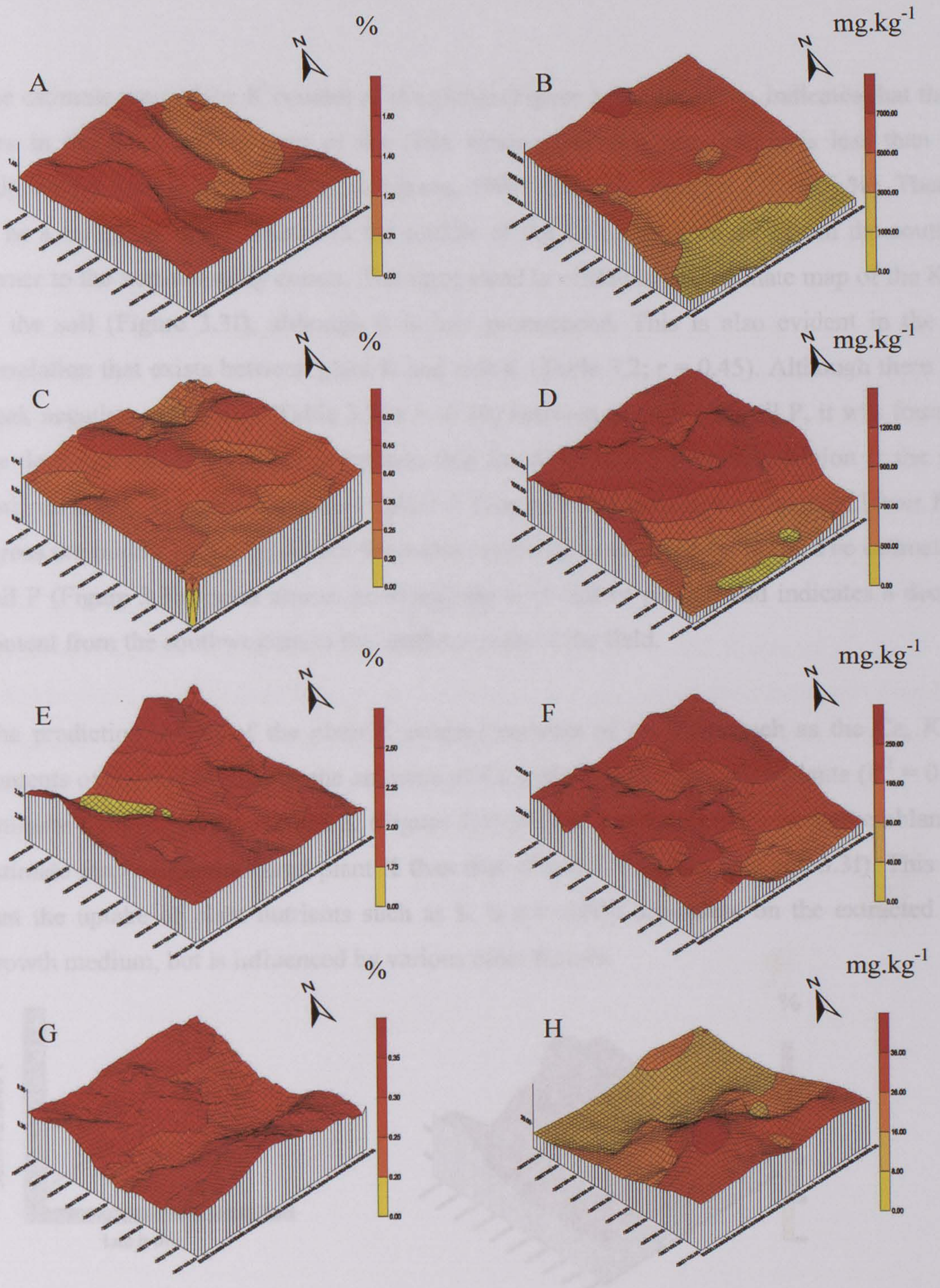

Figure 3.3 Maps of the kriged estimates of the (A) Ca, (C) Mg, (E) K and (G) P contents of the plants and (B) Ca, (D) Mg, (F) K and (H) P contents of the soil.

The estimate map of the K content of the plants (Figure 3.3e), however, indicates that there is an area in the northwesterly part of the field where plant K concentration is less than 1.75 %, indicating a deficiency (Reuter & Robinson, 1997: Adequate range = 2.0 – 3.5 %). There seems to be a trough of low K values in the middle of the field that decreases from the southeasterly corner to the northwesterly corner. The same trend is visible in the estimate map of the K content of the soil (Figure 3.3f), although it is less pronounced. This is also evident in the positive correlation that exists between plant K and soil K (Table 3.2; r = 0.45). Although there is a very weak negative correlation (Table 3.2; r = -0.10) between plant P and soil P, it was found during the development of the semi-variograms that the direction of greatest variation is the same for both variables. The estimate map of plant P (Figure 3.3g) indicates a trough of lower P content across the middle of the field from the northeastern to the southwestern side. The estimate map of soil P (Figure 3.3h) bears almost no resemblance to that of plant P and indicates a decline in P content from the southwestern to the northern parts of the field.

The prediction model of the plant K content consists of variables such as the Ca, K and silt contents of the soil as well as the amounts of Ca and Mg taken up by the plants ($R^2 = 0.58$). The estimate map of predicted plant K (Figure 3.4) yielded a much better visual resemblance to the estimate map of the measured plant K than that of soil K (Figures 3.3e and 3.3f). This indicates that the uptake of plant nutrients such as K is not solely dependent on the extracted K in the growth medium, but is influenced by various other factors.

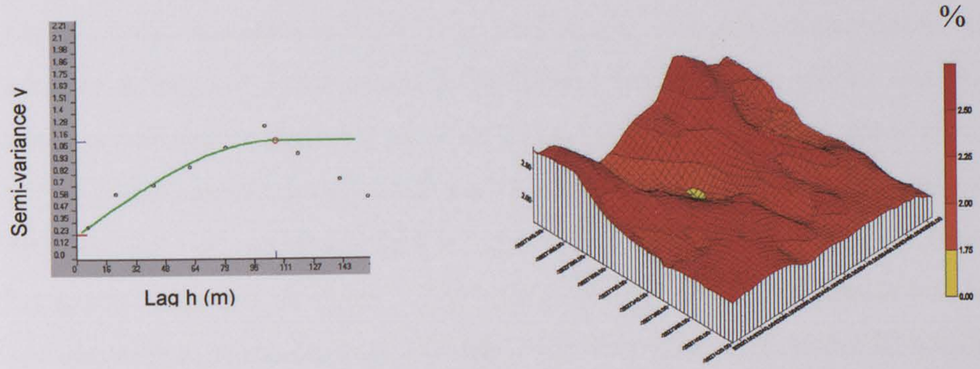

Figure 3.4 Experimental semi-variogram and estimate map of the predicted K in the plants.

3.5 Conclusions

Statistical analyses indicated that the two soil types affected soil and plant properties to different degrees. For some properties (*e.g.* pH, Mg content of the soil and electrical resistance) a distinct bi-modal population resulted, while there was hardly any effect on other properties (all plant element concentrations and organic C, P and K contents of the soil). A linear regression analysis, in general, showed poor correlations between the plant element uptake and soil properties, but with the use of a multiple regression analysis the major plant and soil properties that influenced the uptake of elements by plants were established. Geostatistical procedures allowed the estimation of elements to construct maps in order to demonstrate the spatial variability of plant and soil properties. The majority of variables showed considerable variation and highly variable autocorrelation lengths. This study has shown that there is little or no resemblance when comparing the spatial distribution of lucerne plant Ca, Mg, K and P contents with those of the soil. However, making use of a multiple regression equation, good agreement was found between the spatial distribution of measured and predicted plant K. This emphasizes the fact that the uptake of elements by plants is not solely dependent on the concentrations thereof in the soil solution, but on other factors as well.

CHAPTER 4

SPATIAL RELATIONS OF PLANT ELEMENT UPTAKE AND YIELD OF A LUCERNE STAND OVER TIME

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4.1 Abstract

In general, agricultural fields are managed as uniform units, ignoring spatial and temporal relations between plant element uptake and yield. This study was conducted from June 2001 to February 2002 on a two-year-old lucerne stand and explores the spatial relationships between nutrient uptake and green biomass yield during both winter and summer growing seasons, as well as the temporal variation of lucerne yield during a growing season using geostatistical procedures. Green biomass yield was determined on six occasions at 162 sampling points across the field, while soil and plant sampling and analyses were conducted once in June 2001. Although the lucerne stand contains on average adequate concentrations of Ca, Mg, P and K, areas of K deficiency did occur in the field during both the winter and summer seasons. Weak linear correlations exist between plant elements and yield. Similarities were discernable between winter and summer spatial variations of plant Ca, Mg, P and K. Significant correlations existed between soil and plant Mg and K, and in the case of Mg, exhibited clear spatial similarities. Temporal variations in lucerne yield were observed, with the lowest and highest yields in June and September, respectively. Although there were large differences in spatial variation of lucerne yields across the harvesting events, similar spatial patterns were evident. A clear resemblance between spatial plant K and yield existed, probably because the deficiency in plant K was a dominant factor in causing spatial variation in yield. Although this study revealed spatial and temporal patterns in plant element uptake and yield of a lucerne stand at a specific location, the

results illustrate some useful practical aspects relevant to site-specific management of lucerne stands.

4.2 Introduction

Spatial and temporal variation of soil properties causes uncertainty in agricultural decision-making, but this variation is manageable if it is significant, controllable and predictable (Cook & Bramley, 2000). Traditionally, spatial variation is managed by grouping properties together in seemingly homogeneous units and assuming variability within the units to be purely random or uncorrelated. This results in the field being managed uniformly for activities such as sowing, and fertilizer and pesticide application, ignoring the soil spatial variability and hence the site-specific crop requirement (McBratney & Pringle, 1997). Site-specific management, unfortunately, requires a large investment in collecting the data required to make informed decisions at this scale, and prohibits the adoption of such an intensive management programme. Today, however, the spatial variation within a field can be managed with the use of geostatistical techniques. Based on the premise that the spatial variability of crop yield is influenced by spatial variability in soil factors at a similar scale, researchers have begun to examine the patterns observed in crop yield maps to identify potential management zones within a field as well as to improve sampling scheme designs (Stafford, Ambler, Lark & Catt, 1996; Venter, Beukes, Claassens & Van Meirvenne, 2003a; Frogbrook, Oliver, Salahi & Ellis, 2002). According to Boydell and McBratney (2002), stable yield zone patterns can be identified by using multi-seasonal yield maps.

In South Africa, lucerne (*Medicago sativa* L.) is grown under a wide range of climatic conditions, under dryland and irrigation. According to Fick, Holt and Lugg (1988), the lucerne crop usually shows a corresponding response to a constantly changing environment, which depends on factors such as the age, growth stage, prior condition and genotype of the crop. The objectives of this study were (1) to explore the spatial relationships between nutrient uptake and green biomass yield during both winter and summer growing seasons, and (2) to investigate the temporal variation of lucerne yield during a growing season to identify yield zone patterns in the field.

4.3 Materials and Methods

4.3.1 Field and analytical methods

The study was conducted on an 18 ha lucerne stand in the Brits district in the North West Province of South Africa (Venter *et al.,* 2003a). The study area was selected because of its geographic location where good lucerne production is possible throughout the year. A rectangular area of 160 m X 140 m was demarcated as the experimental plot. The lucerne stand was two years old when the study commenced and was irrigated with a sprinkler irrigation system. Seventy-two sampling points were laid out on a 20 m square grid with an additional 90 sampling points laid out on a 2.5 m square grid at six randomly selected node points to ensure that the total spatial structure would be identified.

Harvesting was done by cutting above-ground plant parts at an early flowering stage within a 0.6 m square at each of the sampling points and weighing to determine green biomass yield. Yield was determined on six occasions: June, August, September, October and November 2001 and again in February 2002. Mean yields per harvest were calculated from data of all sampling points. Whole plant samples from the June (winter) and February (summer) harvests were analysed for calcium (Ca), magnesium (Mg), phosphate (P) and potassium (K) content using standard methods (Agri Laboratory Association of Southern Africa, 1998). Soil samples taken in June 2001 at the sampling points were analysed for exchangeable K, Ca, Mg and sodium (Na), P status, organic C content, as well as for pH(H_2O), electrical resistance, texture and water retention (at -33kPa) using standard methods (Non-Affiliated Soil Analysis Work Committee, 1990). Details of the experimental layout, sampling and analytical procedures are reported elsewhere (Venter *et al.*, 2003a). Nitrogen (N) was not considered as it varies spatially with a very short correlation length (Cahn, Hummel & Brouer, 1994) and because of analytical cost considerations.

4.3.2 Statistical methods

For the purpose of this paper, two soil properties (Mg and K content) were included to illustrate the influence of soil properties on plant element uptake. The spatial relations between plant element uptake and soil properties are reported elsewhere (Venter, Beukes, Claassens & Van Meirvenne, 2003b). Descriptive statistical analyses were performed to obtain information on the frequency distribution, standard deviation and coefficients of variation of the plant and soil chemical data and yield. All properties displayed normal distributions and no transformations were necessary. A correlation matrix was developed to establish the linear correlations between the plant and soil elements, as well as biomass yield, after which an all-possible regression analysis was performed to measure the extent to which the uptake of nutrients influenced yield of the lucerne stand. A two-sample t-test (Snedecor & Cochran, 1967) was used to indicate statistical differences between the concentrations of plant nutrients, as well as between the various yields of the stand when comparing the winter and summer growing seasons.

Geostatistical analyses were performed to generate maps of the spatial variation of the plant and soil properties, as well as yield (Hunt, 2002). All the properties were normally distributed and standard semi-variograms and ordinary kriging were used to generate the estimated values. All estimates were contoured and mapped (Golden Software Inc., 1995) to illustrate the spatial variability of properties.

4.4 Results and Discussion

Table 4.1 shows the mean concentration of the nutrients Ca, Mg, P and K in the plants, as well as the Mg and K contents of the soil, and indicates that lucerne has a higher uptake of K than of the other nutrients. According to Lanyon and Griffith (1988), lucerne reflects a degree of luxury consumption of K, which means that not all the K removed in the crop is essential for plant growth. The observed mean nutrient concentrations in the plants are, according to Reuter and Robinson (1997), in the “adequate” to “high” range, although there were some spots in the field, especially for K, that showed deficiencies. The correlation matrix (Table 4.2) shows weak linear correlations between the plant elements and yield while stronger correlations exist between the soil properties and both the plant elements and yield. Using all the plant elements, an all-possible regression analysis indicated that a model that included all four elements could explain only 18 % of the variation in yield of the June harvest and 29 % of the variation in yield of the February harvest (Table 4.3).

Table 4.1 The statistical description of plant and soil properties.

Plant properties (%)		**Min.**	**Max.**	**Mean**	**Median**	**Std. Dev.**	**CV**
June 2001	Ca	0.92	1.8	1.35	1.34	0.18	0.13
	Mg	0.2	0.47	0.32	0.32	0.05	0.17
	P	0.18	0.40	0.31	0.31	0.04	0.13
	K	1.30	3.49	2.22	2.28	0.39	0.18
February 2002	Ca	0.86	1.93	1.43	1.43	0.24	0.16
	Mg	0.24	0.80	0.45	0.46	0.10	0.23
	P	0.12	0.52	0.29	0.31	0.09	0.31
	K	0.62	3.02	1.75	1.74	0.42	0.24
Yield (t ha^{-1})							
2001	June	1.59	10.72	5.69	5.42	2.03	0.36
	August	3.00	18.22	9.55	9.35	2.75	0.29
	September	3.30	22.42	11.61	11.11	4.49	0.39
	October	3.39	18.00	10.37	10.45	2.90	0.28
	November	2.54	15.99	8.66	8.46	2.83	0.33
2002	February	2.07	16.94	9.65	9.91	3.49	0.36
Soil properties (mg kg^{-1})							
June 2001	Mg	399	1917	1116	945	451	0.40
	K	94	468	222	221	65	0.30

Table 4.2 The correlation matrix of plant and soil properties and lucerne yield.

		Plant analysis - June 2001					*Plant analysis February - 2002*				
		Ca	**Mg**	**P**	**K**	**Yield**	**Ca**	**Mg**	**P**	**K**	**Yield**
Plant analysis – June 2001	**Ca**	1									
	Mg	0.05	1								
	P	0.38	-0.02	1							
	K	0.08	-0.61	0.07	1						
	Yield	0.26	-0.21	0.23	-0.02	1					
Soil	**Mg**	-0.30	0.49	-0.23	-0.20	-0.62					
	K	-0.15	-0.08	-0.12	0.45	-0.31					
Plant analysis – February 2002	**Ca**						1				
	Mg						0.28	1			
	P						0.29	0.57	1		
	K						0.07	0.02	0.44	1	
	Yield						0.21	-0.40	-0.15	-0.06	1

Table 4.3 Regression models including all leaf elements.

Harvest	Variables	% Variance explained (r^2)
June 2001	Ca, Mg, P, K	18
February 2002	Ca, Mg, P, K	29

A two-sample t-test indicated that there are highly significant differences between winter and summer values of the four elements, as well as yield (Table 4.4). These results appear to contradict the similarities in spatial variations to be discussed in Figures 4.2a to 4.2i. However, it must be borne in mind that classical statistical procedures, such as those used to obtain the results in Table 4.4, ignore any spatial correlations between field properties. Lucerne, unlike many tree species, has no true physiological rest period (McKenzie, Paquin & Duke, 1988), although it may become dormant to span unfavourable periods caused by cold, heat or drought. Yield increased during the spring months and reached its peak in September, after which it decreased into summer (Figure 4.1). According to McKenzie *et al.* (1988) this decline in production of lucerne during hot weather is commonly referred to as the "summer slump". A number of studies have been done on this phenomenon, which have resulted in several explanations. Fick *et al.* (1988) quote several studies that *inter alia* suggest (1) a combination of changes in temperature, photoperiod and water deficit, and (2) the association of shorter growth intervals and faster phenological development in summer, as causes for the summer yield decline.

Table 4.4 A two-sample t-test between the winter and summer plant analyses and lucerne yield.

	Mean plant properties				
	Ca (%)	**Mg (%)**	**P (%)**	**K (%)**	**Yield (t ha^{-1})**
June 2001	1.35	0.32	0.31	2.22	5.69
February 2002	1.43	0.45	0.29	1.75	9.65
t Value	-2.16*	-13.84***	3.13**	10.31***	-12.50***

t(0.001)(160 d.f.) = 3.29***; t(0.01)(160 d.f.) = 2.58**; t(0.05)(160 d.f.) = 1.96*

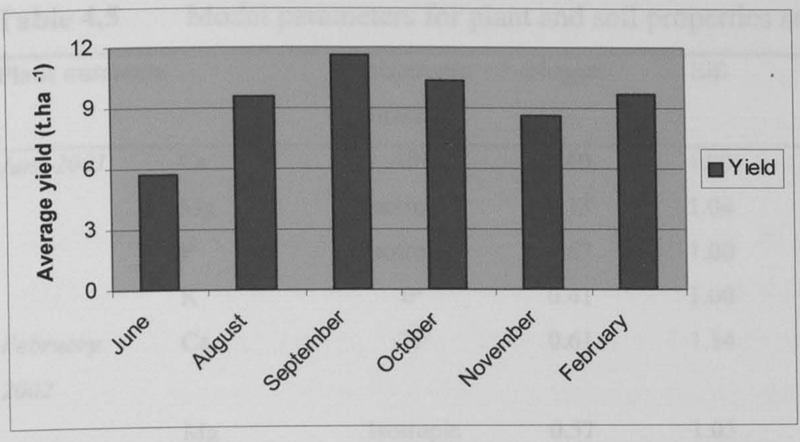


Figure 4.1 Mean yield of six harvests from June 2001 (mid-winter) to February 2002 (summer).

4.4.1 Spatial analyses

The field has a slight northeasterly slope of approximately 2 % (Venter et al., 2003a). The semi-variograms and spatial maps of plant and soil properties are given in Figure 4.2 and those of yield in Figure 4.3. Model parameters for plant and soil properties and yield are given in Table 4.5. In the case of anisotrophy, two ranges are indicated in the latter table. All the semi-variograms reached an upper boundary, i.e. a sill at a certain lag distance or range. The range is reflected as the maximum separation distance for which sample pairs remain correlated (Webster & Oliver, 2000). In practical terms this means that as spatial variability increases, the range decreases. The majority of winter plant Ca values occurred in the 0.70 – 1.20 % and 1.20 – 1.40 % classes, resulting in relatively low spatial variation (Figure 4.2a). However, in summer, spatial variability of plant Ca increased as Ca uptake increased, with a majority of values in the higher 1.40 – 1.60 % class, leaving two troughs of lower values (1.20 – 1.40 % class) (Figure 4.2b). The increase in spatial variability of summer Ca values is also reflected in the semi-variograms having a shorter range and a higher nugget variance (Table 4.5; Figures 4.2a & 4.2b). When comparing Figures 4.2a and 4.2b, some similarities are discernable between the spatial winter and summer plant Ca values. For example, ridges of high Ca values exist on both maps along the western border and the northern side. A trough of low values is also evident along the upper eastern border.

Table 4.5 Model parameters for plant and soil properties and yield.

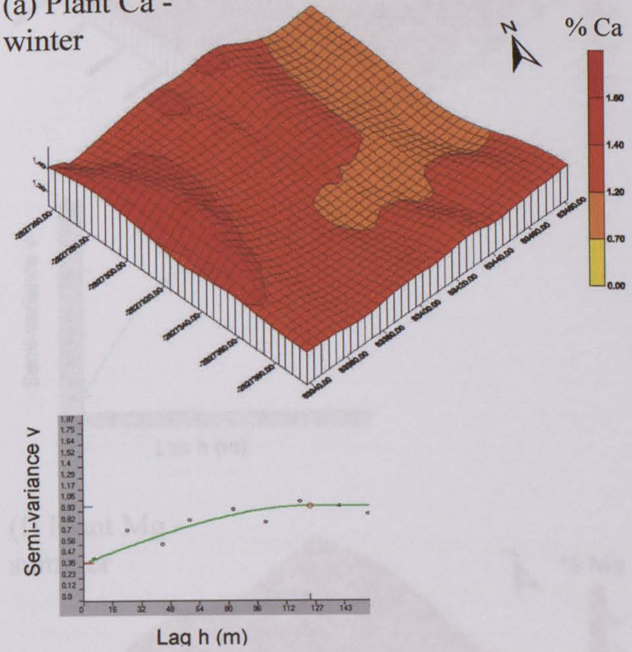
Plant nutrients		Anisotropic direction	Nugget	Sill	Long range (m)	Short range (m)
June 2001	Ca	40°	0.40	1.00	125	55
	Mg	Isotropic	0.13	1.04	61	-
	P	Isotropic	0.67	1.00	74	-
	K	0°	0.41	1.00	95	59
February 2002	Ca	20°	0.61	1.14	110	45
	Mg	Isotropic	0.57	1.05	86	-
	P	Isotropic	0.86	1.10	45	-
	K	40°	0.33	1.00	57	32
Soil nutrients						
	Mg	Isotropic	0.18	0.99	104	-
	K	Isotropic	0.17	0.82	75	-
Yield						
2001	June	140°	0.34	0.99	134	43
	August	120°	0.47	0.99	192	48
	September	120°	0.26	1.00	76	40
	October	Isotropic	0.44	0.99	92	-
	November	140°	0.32	0.99	122	32
2002	February	Isotropic	0.09	1.03	30	-

Unlike plant Ca, spatial plant P exhibits higher values in winter than in summer (compare Figures 4.2c & 4.2d), with summer P also showing higher variability. The lower summer P values may be the result of the so-called "dilution factor" because of the larger summer biomass yields (Figure 4.1; Table 4.1). There is little resemblance between winter and summer spatial values, although a trough (Figure 4.2c) and a partial trough (Figure 4.2d) of low values are discernable in an east-west direction in the centre of the field. The winter and summer spatial variation of plant Mg (Figures 4.2e & 4.2f) also bears some resemblance, with similar patches of high and low values along the northwestern and southeastern borders, respectively. Winter Mg values are also lower than summer values. Although variable in nature, the winter or summer plant Ca, P and Mg were above the deficiency values of Reuter and Robinson (1997) ($Ca < 0.70$; $P < 0.20$; $Mg < 0.20$ %). Although the range for Mg in the summer is slightly longer than in winter, the nugget for the summer analysis is much higher (Table 4.5). The bigger nugget variance is associated with spatially dependent variation occurring over smaller distances than the smallest sampling interval and measurement error (Webster & Oliver, 2000) (Table 4.5; Figures 4.2e & 4.2f). The estimate map of soil Mg (Figure 4.2g) shows a very good resemblance to that of the plant Mg in both winter and summer (Figures 4.2e & 4.2f). Table 4.2 shows that there is a relatively high correlation between soil and plant Mg (r = 0.49), as well as K (r = 0.45), although there is not such a clear visual resemblance between the spatial soil and plant K (compare Figures 4.2j with 4.2h and 4.2i). The high correlations may be due to the high uptake rate of both elements through the plant membrane and a high mobility throughout the entire plant. The winter and summer spatial values for plant K also bear some similarity (compare Figures 4.2h & 4.2i) with a major increase in spatial variability (and a decease in range) in summer plant K. Summer plant K values were much lower than winter values, with areas of K deficiency (K < 1.75 %: Reuter & Robinson, 1997) in both seasons, but with very marked areas of deficiency during summer. The lower summer K values may also be due to a "dilution effect" caused by the more vigorous summer plant growth. In work reported previously, a model for the prediction of K uptake by lucerne consisted of factors such as the exchangeable Ca, K and silt content of the soil, as well as the amounts of Ca and Mg taken up by the lucerne, and explained 58 % of the variation in plant K for this field (Venter et al., 2003b). It was concluded that the uptake of plant nutrients, such as K, is not solely dependent on the availability of the nutrient in the growth medium, but is influenced by various other factors as well.

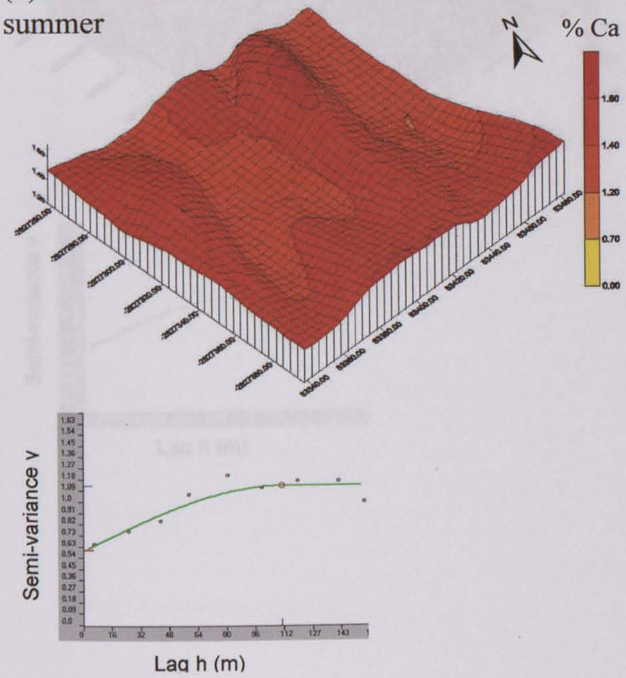
Temporal and spatial variations in lucerne yield are depicted in Figures 4.3a to 4.3f. The semi-variograms indicate that the direction of anisotrophy stays the same throughout the year except in the case of October and February (Figures 4.3d & 4.3f) where no preferred long and short-range directions could be identified and isotropic semi-variograms were modelled. Areas of smaller and larger yields generally vary across the six harvesting incidents with a trough of lower yields discernable towards the northwestern side of the stand for each yield map. The pattern of lowest and highest yields in June and September, respectively, can be observed in Figures 4.3a and 4.3c (see also Figure 4.1). Unlike the results of Frogbrook *et al.* (2002), the shapes of the variograms were dissimilar, yielding for example, highly variable ranges of spatial correlation (Figures 4.3a – 4.3f; Table 4.5). A direct implication of this finding is that sampling intensity should be varied depending on the time of sampling. There is a clear visual resemblance between the plant K maps

(Figure 4.2h & 4.2i) and the matching yield maps (Figure 4.3a & 4.3f). As previously mentioned, areas of deficient plant K were evident and apparently this deficiency was the major cause of spatial variation in yield.

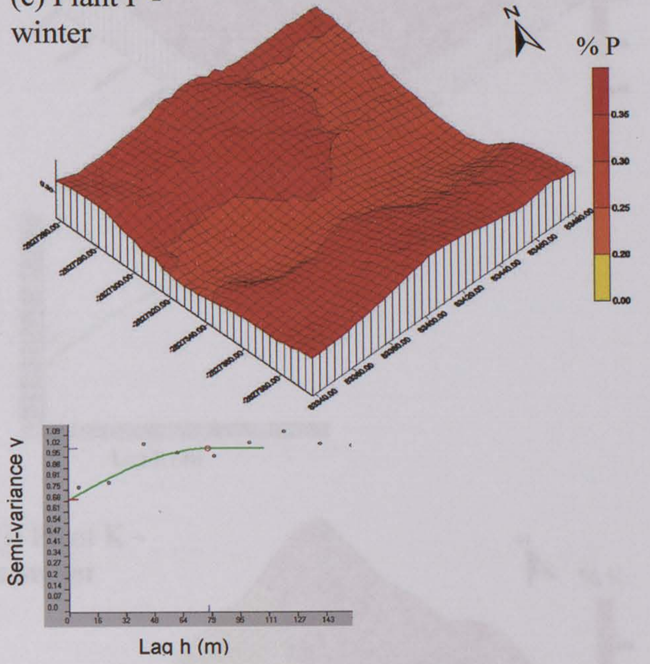
(a) Plant Ca - winter



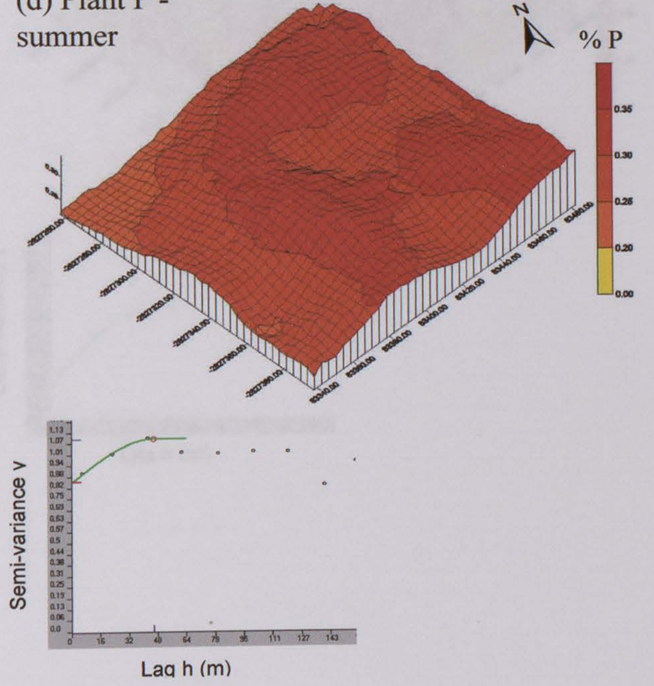
(b) Plant Ca - summer



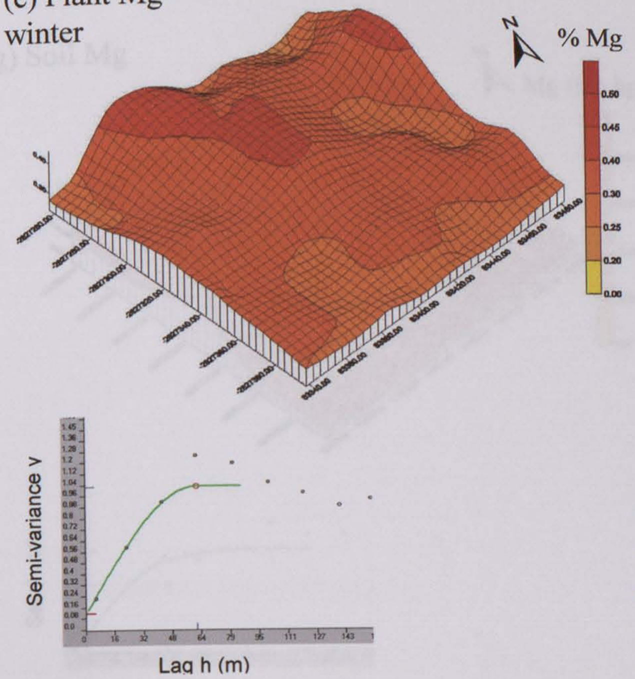
(c) Plant P - winter



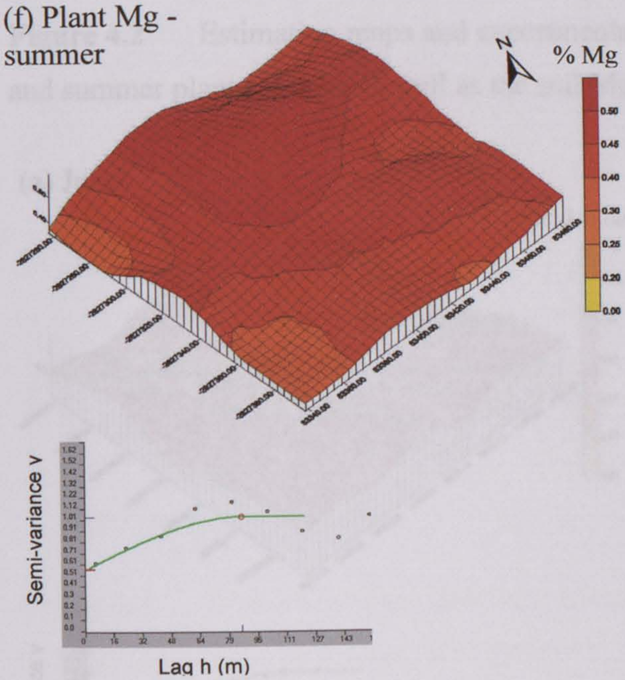
(d) Plant P - summer



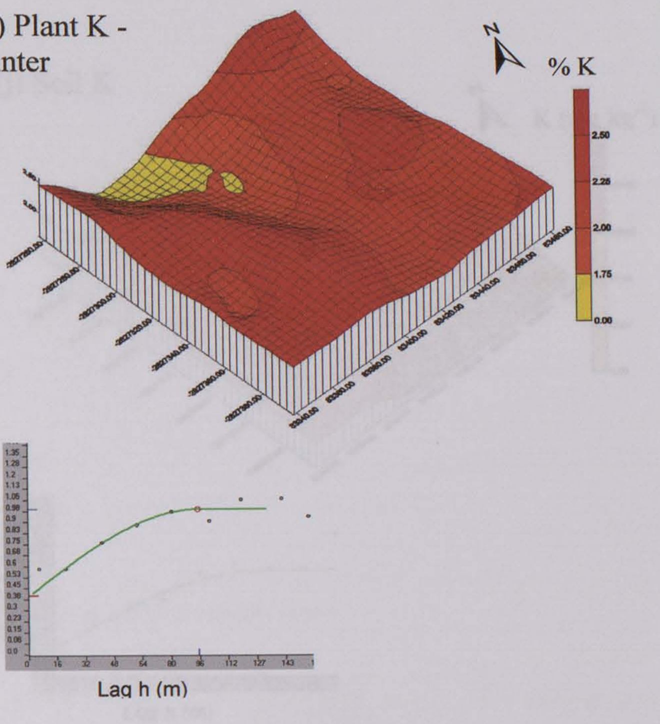
(e) Plant Mg - winter



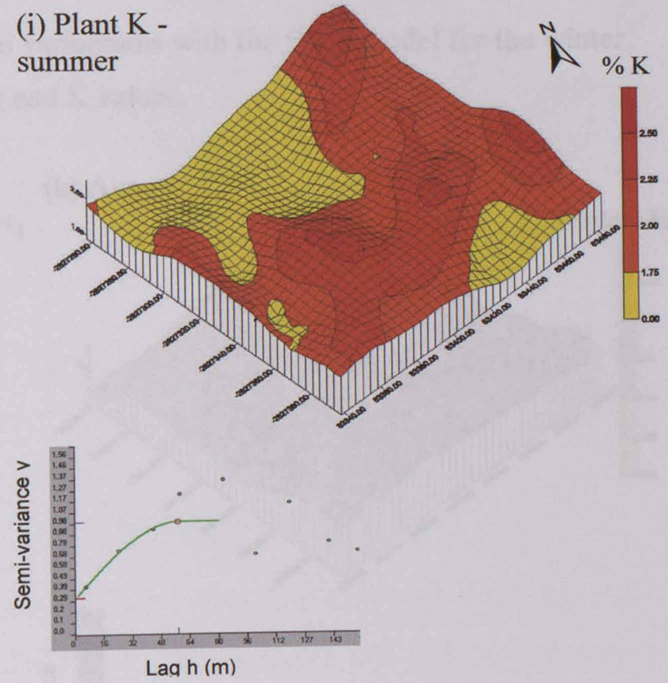
(f) Plant Mg - summer

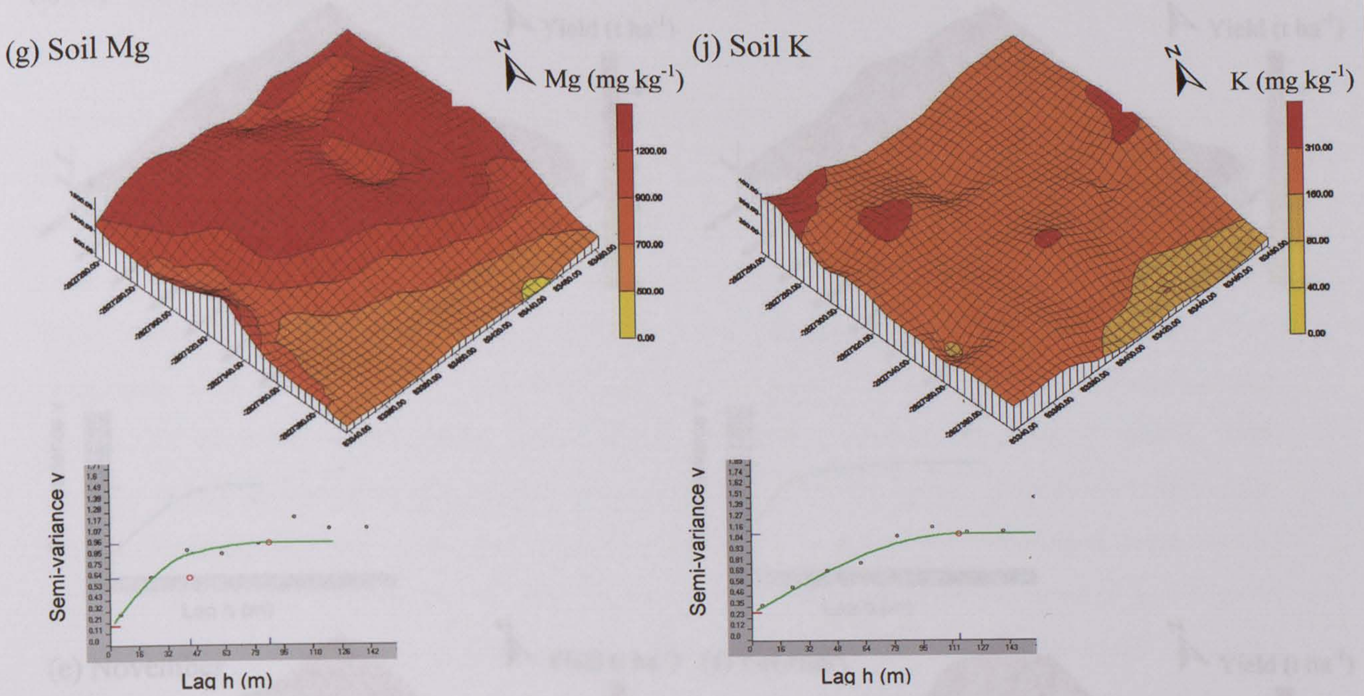


(h) Plant K - winter



(i) Plant K - summer

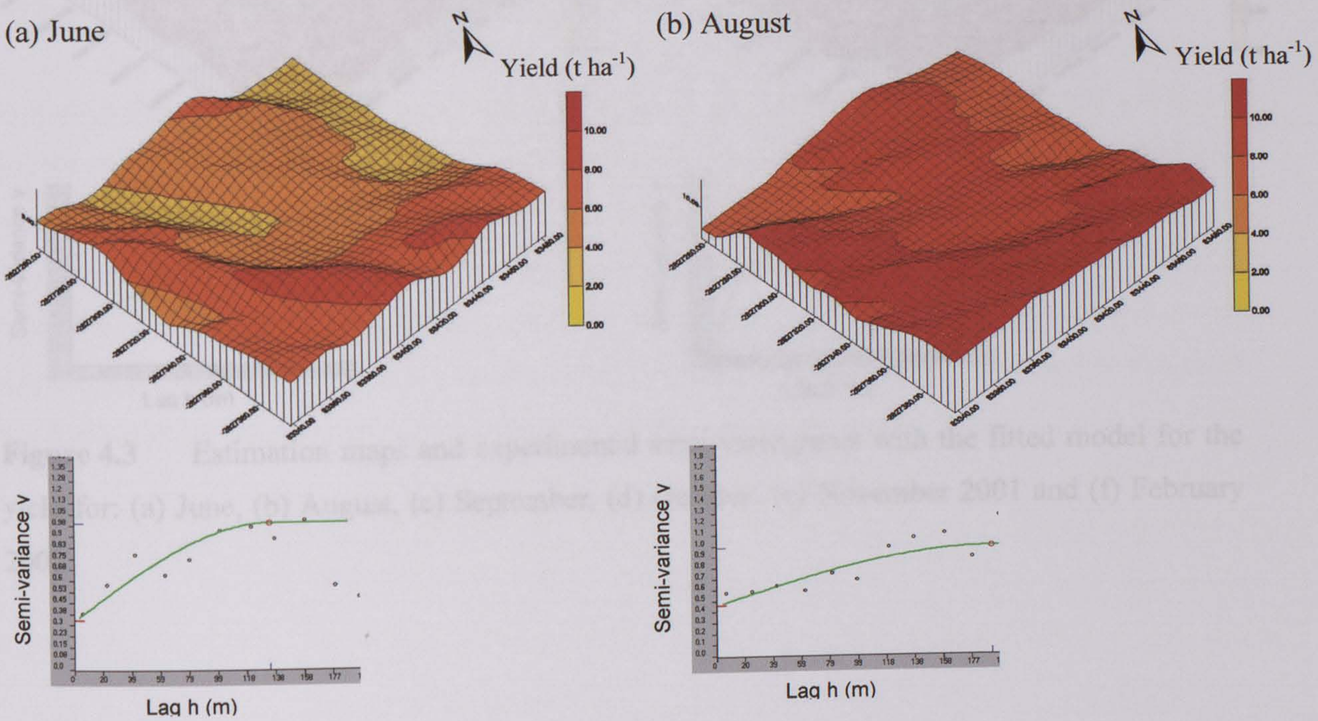




(g) Soil Mg

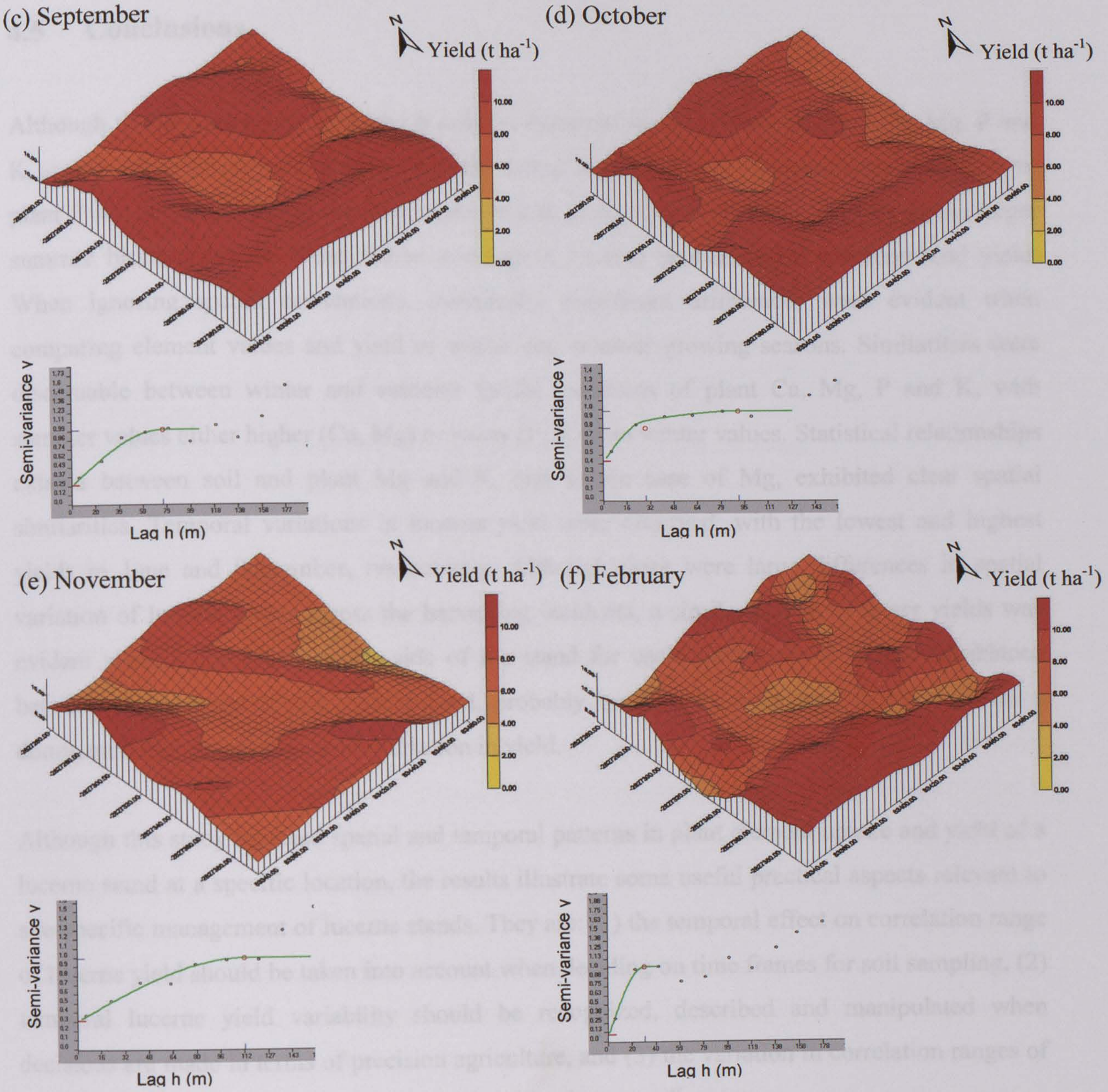
(j) Soil K

Figure 4.2 Estimation maps and experimental variograms with the fitted model for the winter and summer plant analyses as well as the soil Mg and K values.



(a) June

(b) August


(c) September

(d) October

(e) November

(f) February

Figure 4.3 Estimation maps and experimental semi-variograms with the fitted model for the yield for: (a) June, (b) August, (c) September, (d) October, (e) November 2001 and (f) February 2002.

4.5 Conclusions

Although the lucerne stand contains on average adequate concentrations of plant Ca, Mg, P and K, areas of K deficiency did occur in the field during both the winter and summer seasons. Lower plant P and K values during summer could be due to the "dilution effect" exerted by the larger summer biomass yields. Weak linear correlations existed between plant elements and yield. When ignoring spatial correlations, statistically significant differences were evident when comparing element values and yield of winter and summer growing seasons. Similarities were discernable between winter and summer spatial variations of plant Ca, Mg, P and K, with summer values either higher (Ca, Mg) or lower (P, K) than winter values. Statistical relationships existed between soil and plant Mg and K, and in the case of Mg, exhibited clear spatial similarities. Temporal variations in lucerne yield were observed, with the lowest and highest yields in June and September, respectively. Although there were large differences in spatial variation of lucerne yields across the harvesting incidents, a similar trough of lower yields was evident towards the northwestern side of the stand for each yield map. A clear resemblance between spatial plant K and yield existed, probably because the deficiency in plant K was a dominant factor in causing spatial variation in yield.

Although this study revealed spatial and temporal patterns in plant element uptake and yield of a lucerne stand at a specific location, the results illustrate some useful practical aspects relevant to site-specific management of lucerne stands. They are: (1) the temporal effect on correlation range of lucerne yield should be taken into account when deciding on time frames for soil sampling, (2) temporal lucerne yield variability should be recognized, described and manipulated when decisions are made in terms of precision agriculture, and (3) the variation in correlation ranges of the various plant elements should be considered in plant sampling patterns.

CHAPTER 5

SPATIAL VARIATION OF SOIL AND PLANT PROPERTIES AND ITS EFFECTS ON THE STATISTICAL DESIGN A OF A FIELD EXPERIMENT

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5.1 Abstract

Natural soil variability, or previous land-use practices, can significantly reduce the ability to detect experimental treatment differences. Hence, the standard procedure in field experimentation has been to lay out blocks, striving for as homogeneous conditions as possible among plots of the same block. The classical procedures of, *inter alia*, replication, blocking and randomization have assumed spatial and temporal independence among the points of determination of any particular soil or plant property. However, geostatistical concepts dictate that a spatially dependent variance structure exists for observations of a particular property, whereby nearby observations are more similar than those taken further apart. The present study was conducted on an 18-ha lucerne stand in which a 100 m X 140 m experimental area was demarcated. To determine spatial characteristics of soil and plant properties, 48 sampling points (nodes) were laid out on a 20-m square grid with an additional 75 points on a 2.5-m grid at five random node points. A randomized complete block (RCB) design trial was superimposed on the geostatistical grid design and consisted of seven pseudo (i.e. non-existent) treatments, replicated four times. Soil and plant samples were taken at all sampling points and plots in June 2001 and analyzed for various properties, including green biomass yield. Analysis of variance of the RCB design revealed statistically non-significant differences among the pseudo treatments for various soil and plant properties, including yield. The conclusion could be made that the experimental field was

homogeneous enough to lay out a standard block design experiment. However, it was found that the estimate map of soil pH(H_2O) showed a clear structure in spatial variability. The question was posed that if the latter spatial variation had been considered, would it have had any effect on the results of this field experiment, for example, in terms of yield? Scrutiny of the latter variability revealed that the standard RCB designs did not provide homogeneous blocks with respect to soil variability. The consequent redesign of the experiment whereby all plots were randomly allocated to treatments and replications, led to dramatically different results: significant differences were obtained for plant and soil properties as a function of the pseudo treatments. From this study it is clear that spatial variability of soil and plant properties can jeopardize the results of a standard block design field experiment. Regarding soil pH(H_2O) as a covariate (since it correlated very well with green biomass yield) and performing an analysis of covariance, no statistical difference (as expected) among treatments was observed for green biomass yield. It is, therefore, recommended that the layout of field experiments should be designed to the cognizance of the spatial variation of a soil property that correlates highly with a chosen response variate. Hence in the final statistical analysis to test for treatment differences, the particular soil property must be treated as a covariate. Consequent experimental results can then be interpreted with much greater confidence.

5.2 Introduction

Agricultural researchers have long understood that the effect of locality, which is often caused by natural soil variability, or previous land-use practices, can significantly reduce the ability to detect experimental treatment differences (Dulaney, Lengnick & Hart, 1994). Present-day agronomic research has reached a point where the treatment effects being tested are small and the degree of accuracy required in such studies cannot easily be obtained with conventional experimental designs (Van Es, Van Es & Cassel, 1989). It is therefore imperative to establish a high level of experimental precision.

The adverse effects stemming from soil heterogeneity can be addressed by (1) conducting the study on uniform land, or (2) controlling the effects of soil variability through experimental design and improved statistical analysis in order to better account for the effect of field variability on experimental results (Van Es *et al.*, 1989). The latter measure includes replication, blocking, randomization, row-and-column designs and methods such as nearest neighbour and trend analysis. In general, such methods improve the detection of treatment effects, although improper block layout may actually adversely affect the analysis of experiments (Van Es & Van Es, 1993). In the presence of a significant spatial correlation over small distances, the assumption of independence between plots is violated and the researcher may be faced with contradictory results. The latter can result in clear differences in crop yields between experimental plots but no significant treatment effect (Fagroud & Van Meirvenne, 2002).

Some work has been done to evaluate the use of geostatistics in the design of agricultural field experiments (Dulaney *et al.,* 1994; Van Es *et al.,* 1989; Fagroud & Van Meirvenne, 2002). According to Dulaney *et al.* (1994), geostatistical techniques have the potential to provide better field characterization, improve plot layout, increase the power of the consequential statistical techniques and can be used to select an optimal sampling strategy for characterization of soil spatial variability at the experimental field site. This is relevant because the costs associated with conducting long-term agricultural experiments make it imperative to obtain at least some level of assurance that the data used to establish field trials are precise enough for their intended purpose.

The hypothesis of this study was that the natural variation of the soil properties would have an effect on the results of a field experiment if the spatial structure of those properties in the field were not taken into consideration when designing the trial. The purpose of this study, therefore, was to quantify the spatial variation of soil and plant properties in relation to a statistically laid out field experiment.

5.3 Materials and Methods

5.3.1 Field and analytical methods

The study was conducted on an 18-ha lucerne stand in the Brits district of the North West Province of South Africa (27°49^lE, 25°33^lS). A rectangular area of 100 m X 140 m was demarcated as a study area and the soil was classified (based on a field survey) as a deep (1000 mm) Shortlands form (Pyramid family) (Soil Classification Working Group, 1991) (USDA Soil Taxonomy; Typic Rhodustults). Forty-eight sampling points (nodes) were laid out on a 20-m square grid with an additional 75 sampling points laid out on a 2.5-m square grid (sampling total = 123) at five randomly selected node points to ensure that the total spatial structure would be identified. All sampling points were georeferenced using a Ground Positioning System (GPS) and marked with flat metal discs. A randomized complete block (RCB) design trial layout was superimposed on the geostatistical grid design and consisted of seven pseudo treatments (i.e. applying no actual treatments) replicated four times. A plot size of 25 m x 20 m was decided on to fit all the plots in the available area of the original lucerne stand.

In June 2001, plant and soil samples were taken at each of the node points. Plant sampling was done by cutting the aboveground plant parts within a 0.6-m square around each of the node points and weighing to determine green biomass yield. Three soil samples were also collected within the 0.6-m square (0 – 300 mm deep) at each of the sampling points and mixed to serve as a composite sample. Sampling of the RCB design was done by cutting a 10 m^2 area of plants in each of the plots and weighing the samples to determine green biomass yield. Sub-samples were taken for analysis purposes. In each of the plots a composite soil sample was taken of the 0 – 300 mm layer.

Plant samples were analyzed for calcium (Ca), magnesium (Mg), phosphorus (P) and potassium (K) using standard methods (Agri Laboratory Association of Southern Africa, 1998). Soil samples were analyzed for pH(H_2O), organic carbon (C), P (Ambic), Ammonium acetate extractable Ca, K, Sodium (Na), Mg, electrical resistance, particle size and water retention using standard methods (Non-Affiliated Soil Analysis Work Committee, 1990).

5.3.2 Statistical methods

Descriptive statistical analyses were performed to obtain information on the frequency distribution, standard deviation and coefficient of variation of the plant and soil chemical properties and yield. All properties displayed acceptably normal distributions with homogeneous treatment variances and no transformations were necessary. Analyses of variance (ANOVA) were used to test for differences between pseudo treatments for all plant and soil properties using the statistical program GenStat (GenStat, 2000). Treatment means were separated using Fishers' protected t-test least significant difference (LSD) at the 5 % level of significance (Snedecor & Cochran, 1980).

Three different experimental designs were superimposed on the 28 experimental plots (Table 5.1); the first one (ANOVA 1) blocked in the NE-SW direction, with 4 treatments randomly allocated to each of the 7 blocks and the second (ANOVA 2) blocked in the NW-SE direction, with 7 treatments randomly allocated to each of the 4 blocks (Figure 5.1). Both experimental layouts were based on an RCB design. It is obvious from the spatial variability of soil pH(H_2O) (Figure 5.1) that the standard way of blocking either in the NE-SW or NW-SE directions, would not provide homogeneous blocks with respect to soil variability. Consequently, for the third experiment, a completely random design was chosen and the 28 plots randomly allocated to 7 treatments and 4 replications (ANOVA 3). This meant a random distribution of plots over the experimental area (Figure 5.1). An analysis of covariance was also performed using pH(H_2O) as a covariate to eliminate the linear effect of soil pH on yield.

Table 5.1 ANOVA of three different experimental designs.

	ANOVA 1	ANOVA 2	ANOVA 3
	RCBD	RCBD	CRD
	4 treatments in 7 blocks	7 treatments in 4 blocks	7 treatments, 4 replicates
Source of variation	df	df	df
Block	6	3	-
Treatment	3	6	6
Error	18	18	21
TOTAL	27	27	27

RCBD – Randomized Complete Block Design

CRD – Completely Random Design

Geostatistical analyses were performed on the grand total (123) number of samples to generate a map of the spatial variation of the soil pH(H_2O) using the ArcGIS Geostatistical Analyst extension (Johnston, Ver Hoef, Krivoruchko & Lucas, 2001). Additional analyses were performed to generate a spatial map for pH(H_2O) making use of sampling points on a 40-m square grid, as well as points on a 7.5-m square grid at the originally selected five node points (sample total = 37).

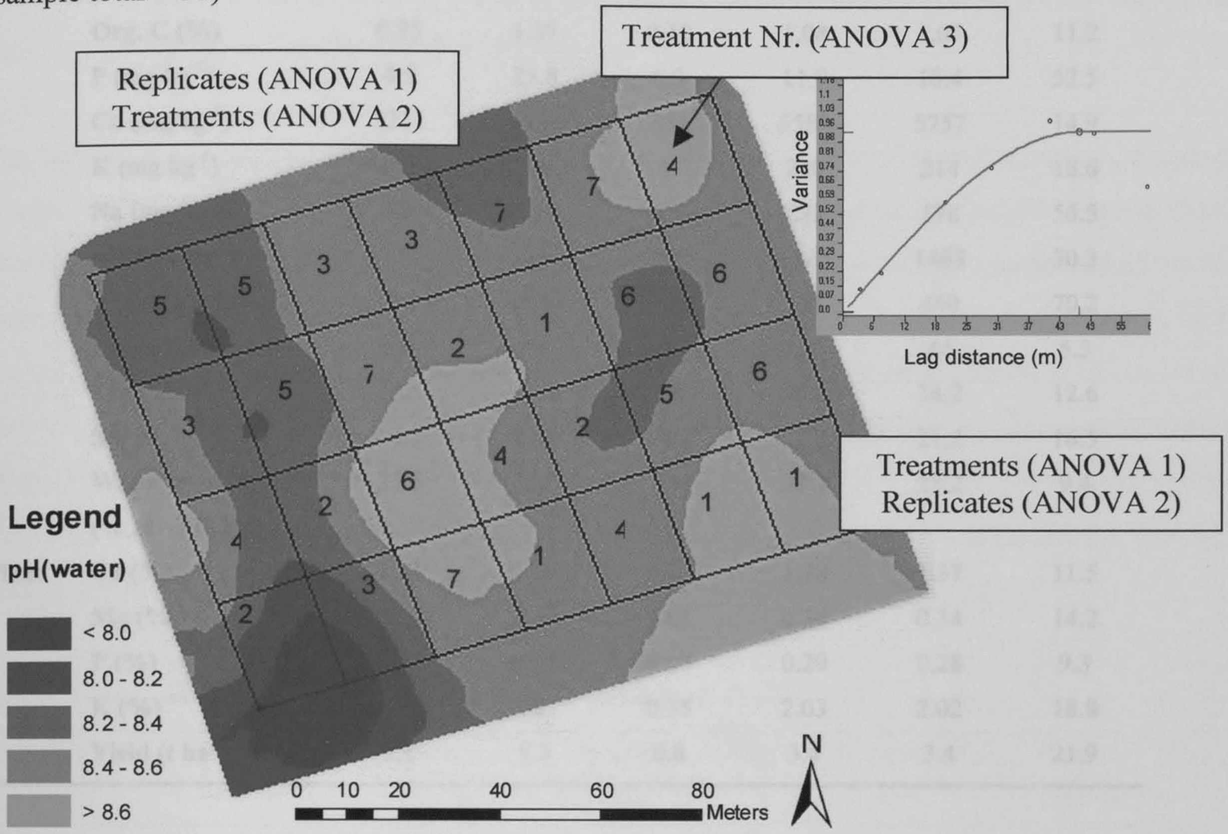

Figure 5.1 Trial layout of the three experimental designs overlaid on the estimate map of soil pH(H_2O).

5.4 Results and Discussion

Table 5.2 shows the mean concentrations of all the soil and plant properties for the 28 experimental plots. The observed mean nutrient concentrations in the plants are, according to Pinkerton, Smith and Lewis (1997), in the "adequate" to "high" range, although there were some spots in the field, especially for K, that showed deficiencies. The correlation matrix (Table 5.3) shows that both pH(H_2O) and Na are highly negatively correlated with yield (Table 5.3; $r = -0.74$ and -0.68, respectively) and that there is a strong relationship between these two soil properties (Table 5.3; $r = 0.76$).

Table 5.2 Statistical description of soil and plant properties.

		Min.	Max.	Std. Dev.	Mean	Median	CV (%)
Soil	**pH(H_2O)**	8.1	9.1	0.2	8.6	8.6	2.5
	Org. C (%)	0.85	1.37	0.12	1.08	1.07	11.2
	P (mg kg^{-1})	4.5	25.8	6.3	11.9	10.4	52.5
	Ca (mg kg^{-1})	3211	6852	834	5588	5757	14.9
	K (mg kg^{-1})	162	308	41	220	214	18.6
	Na (mg kg^{-1})	89	524	126	223	178	56.5
	Mg (mg kg^{-1})	770	2058	400	1323	1463	30.3
	Resistance (ohm)	180	1600	408	581	440	70.2
	Clay (%)	38	46	2	43	44	5.3
	Sand (%)	26.5	44.7	4.4	35.2	34.2	12.6
	Silt (%)	14.3	30.3	3.6	21.8	21.2	16.5
	Water retention (% at –33 kPa)	23.5	33.7	2.6	28.1	28.2	9.4
Plant	**Ca (%)**	1.11	1.66	0.16	1.38	1.37	11.5
	Mg (%)	0.24	0.44	0.05	0.34	0.34	14.2
	P (%)	0.24	0.35	0.03	0.29	0.28	9.3
	K (%)	1.26	2.85	0.38	2.03	2.02	18.8
	Yield (t ha^{-1})	2.1	5.3	0.8	3.4	3.4	21.9

Table 5.3 Correlation matrix of soil properties and lucerne winter yield.

		Soil									Plant
		pH	Org C	Ca	Mg	P	K	Na	Clay	Silt	Yield
Soil	pH	1									
	Org C	-0.71	1								
	Ca	0.37	-0.27	1							
	Mg	0.60	-0.75	0.52	1						
	P	-0.08	0.23	-0.64	-0.41	1					
	K	0.20	0.03	0.16	0.25	0.26	1				
	Na	0.76	-0.63	0.21	0.58	0.09	0.46	1			
	Clay	-0.08	0.13	0.12	-0.04	-0.55	-0.28	-0.16	1		
	Silt	-0.26	0.51	0.36	-0.20	-0.17	0.11	-0.28	0.10	1	
Plant	Yield	-0.74	0.57	-0.39	-0.58	0.09	-0.23	-0.68	-0.04	0.40	1

Figure 5.1 shows the experimental layout of the geostatistical trial and the RCB design of the field experiment overlaid on the estimate map of soil pH(H_2O), as well as the semi-variogram of the latter. The small black dots depict the 123 geostatistical sampling points (nodes) and the grid indicates the layout of the 28 experimental plots.

The spatial structure of pH(H_2O) was determined with the use of a semi-variogram. Kriging interpolation was used to estimate the values at unsampled locations in an ArcGIS Geostatistical Analyst environment (Johnston *et al.*, 2001). An isotropic semi-variogram was modelled as no definite long and short range directions could be identified. The semi-variogram had a very low nugget variance and a range of 36 m (Table 5.4). The low nugget variance indicates that most of the variation in the soil pH(H_2O) was accounted for with this sampling density. The estimate map (Figure 5.1) shows a clear trough of low values in the western part of the field, stretching across the field from the south to the north, as well as patches of high and low values in the middle, southeastern and northeastern parts of the field.

Table 5.4 Model parameters for soil and plant properties.

Variables		**Anisotropic direction**	**Nugget**	**Sill**	**Long range (m)**	**Short range (m)**
Soil	**pH(H_2O)**	Isotropic	0.09	0.82	36	-
	pH(H_2O) – 37points	Isotropic	0.26	0.98	35	-
Plant	**Yield**	170°	0.16	1.01	42	26

The pH(H_2O) of the soil displayed a strong negative relationship with yield (Table 5.3; $r = -0.74$). Lanyon and Griffith (1988) quoted several studies that found yield reductions when (1) heavy rates of lime have been applied, (2) B is potentially limiting, or (3) P is marginal and lime is applied at normal rates. Although soil pH can be influenced by soil texture, organic matter and other soil chemical properties, the optimum pH(H_2O) for maximum lucerne yield ranges from 6.0 to 7.5 (Lanyon & Griffith, 1988). In this study, however, pH values ranged between 8.1 and 9.1 (Table 5.2). This confirms the validity of the pH range reported by Lanyon and Griffith (1988).

Table 5.5 shows that there was no significant treatment differences at the probability level $p \leq 0.05$ for yield either for ANOVA 1 or 2 ($p = 0.707$ and 0.489, respectively). Analyses of variance for all other properties, using the ANOVA 1 and ANOVA 2 structure were also not statistically significant (Table 5.5). The conclusion could be made that the experimental field is homogeneous enough to lay out a standard block design experiment. However, in the discussion of the spatial variation of soil pH(H_2O), spatial heterogeneity of this property became very clear. In actual fact, the standard way of blocking in either of the two directions would not have provided homogeneous blocks with respect to soil variability. The question was then posed: If the observed spatial variation had been considered, would it have had any effect on the results of this field experiment in terms of yield, or for that matter, any of the other properties that were measured? The experimental design of ANOVA 3 (see Figure 5.1) has been an attempt to statistically take the spatial variability of soil pH(H_2O) into consideration. ANOVA 3 (Table 5.5) exhibits significant to highly significant differences ($p \leq 0.05$ or ≤ 0.01) for a number of properties, including yield, as a function of the "treatments", although there were actually no treatments applied. These results have serious implications for the standard method of laying out RCB field trials on what is presumed to be homogeneous land. However, if pH(H_2O) is regarded as a covariate, as suggested by Snedecor and Cochran (1980) for the typical case where a variable (X) is linearly correlated to the final response (Y), the effects of spatial variation can be accommodated. An analysis of covariance was performed whereby treatment biomass yields were adjusted to remove the effects of pH on yield. In this way lower experimental error was obtained, as well as more precise comparisons among treatments. The results of ANCOVA 3 (Table 5.5) shows that the "treatments" had no statistically significant effect ($p = 0.191$) on biomass yield.

Table 5.5 Summary of F probabilities (p) for the three experimental designs and covariance analysis.

	Soil				**Plant**		
Experimental designs	**pH(H_2O)**	**Org. C (%)**	**Ca ($mg.kg^{-1}$)**	**Silt (%)**	**Ca (%)**	**P (%)**	**Yield ($t\ ha^{-1}$)**
ANOVA 1	0.437 NS	0.538 NS	0.729 NS	0.940 NS	0.729 NS	0.168 NS	0.707 NS
ANOVA 2	0.798 NS	0.683 NS	0.391 NS	0.482 NS	0.383 NS	0.967 NS	0.489 NS
ANOVA 3	0.140 NS	0.003**	0.426 NS	0.036*	0.465 NS	0.019*	<0.009**
ANCOVA 3	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	0.191 NS

* - Statistically significant ($p \leq 0.05$)

** - Statistically highly significant ($p \leq 0.01$)

NS – Not statistically significant

n.d. – not determined

The foregoing results are based on a sampling point total of 123 on an area of 100 X 140 m. Out of a sampling time and cost view, such a large number of sample points might be considered as being impractical. When compared to Figure 5.1 (123 sampling points), the estimate map (Figure 5.2; 37 sampling points) has lost some of the spatial variation in soil pH(H_2O). However, the overall spatial trends are still discernable in Figure 5.2.

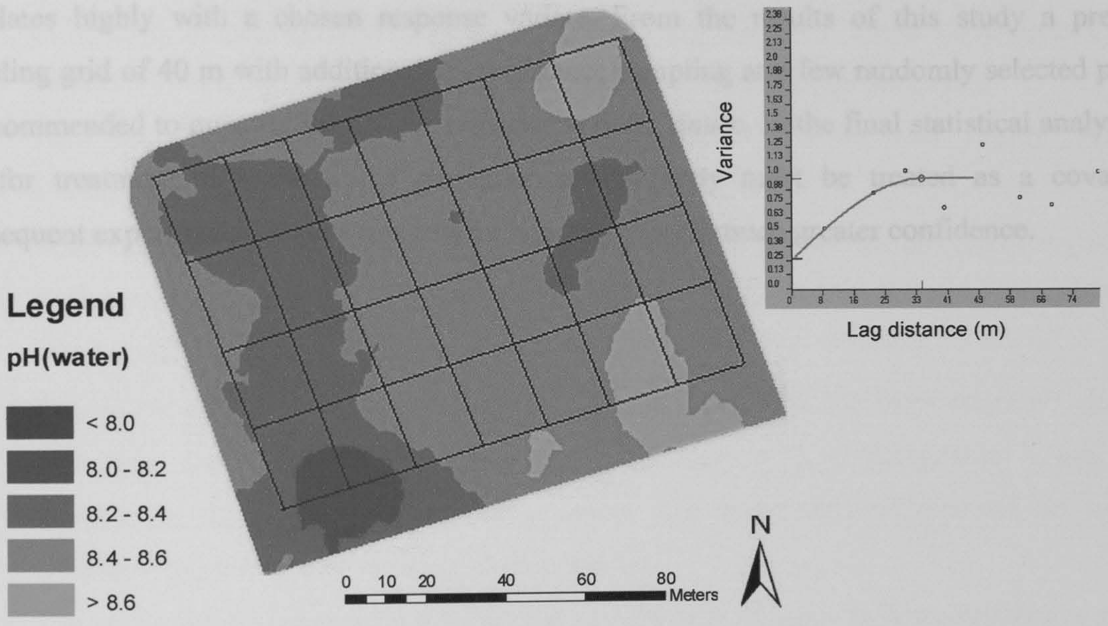

Figure 5.2 Semi-variogram and estimate map of pH(H_2O) using only 37 points.

5.5 Conclusions

Analysis of variance of a randomized complete block design that consisted of pseudo treatments with replications revealed statistically non-significant differences among treatments for various soil and plant properties, including yield. The conclusion could be made that the experimental field is homogeneous enough to lay out a standard block design experiment. A spatial map of soil pH showed a clear structure in spatial variability. The question was posed that if the latter spatial variation had been considered, would it have had any effect on the results of this field experiment, for example, in terms of yield? The consequent redesign of the experiment whereby all plots were randomly allocated to treatments and replications, led to dramatically different results: significant differences were obtained for plant and soil properties as a function of the pseudo treatments. From this study it is clear that spatial variability of soil and plant properties can jeopardize the results of a standard block design field experiment. However, it was found that soil pH(H_2O) correlated very well with green biomass yield. Consequently, regarding soil pH(H_2O) as a covariate an analysis of covariance indicated no statistical difference (as expected) among treatments observed for green biomass yield. It is, therefore, recommended that field experiments should be designed to the cognizance of the spatial variation of a soil property that correlates highly with a chosen response variate. From the results of this study a pre-trial sampling grid of 40 m with additional short distance sampling at a few randomly selected points is recommended to quantify the chosen response variate. Hence, in the final statistical analysis to test for treatment differences, the particular soil property must be treated as a covariate. Consequent experimental results can now be interpreted with much greater confidence.

CONCLUSIONS

The major conclusions of this study can be summarized as follows based on the results from the four objectives.

1. By examining the effects of spatial variation of certain soil properties on the winter yield of a lucerne stand, the following was concluded.

- The two identifiable soils on the study site, although similar in certain aspects, exhibited differences in pH(H_2O), Ca, Mg and dominant clay minerals. These differences caused distinct bi-modal populations of data when subjected to statistical analysis.
- The majority of properties showed considerable variation and highly variable autocorrelation lengths.
- Simple linear regression analyses showed that the soil properties pH(H_2O), organic C, exchangeable Ca and Mg contents are individually well correlated with green biomass lucerne yield.
- A prediction model for lucerne yield ($R^2 = 0.55$) was obtained from stepwise multiple regression analyses. The model had pH(H_2O), organic C, exchangeable K and sand contents as variables. Although soil P status is a major nutrient element for lucerne growth, it did not feature in the prediction model.
- The geostatistical procedures allowed the construction of maps to demonstrate the spatial variability of soil properties and of lucerne yield. The fair resemblance between the measure and predicted yield maps supports the validity of the yield prediction model. The conclusion that the scale of variation of the yield can be related to that of soil properties is supported by this study. This can be useful in designing an appropriate sampling scheme for observing soil properties in future.

2. When the spatial relations between plant element uptake of a lucerne stand and soil properties were explored, the following conclusions could be made.

- Statistical analyses indicated that the two soil types affected soil and plant properties to different degrees. For some properties (*e.g.* pH, Mg content of the soil and electrical resistance) a distinct bi-modal population resulted, while there was hardly any effect on other properties (all plant element concentrations and organic C, P and K contents of the soil).
- A linear regression analysis, in general, showed poor correlations between the plant element uptake and soil properties, but with the use of a multiple regression analysis the major plant and soil properties that influenced the uptake of elements by plants were established.
- Geostatistical procedures allowed the estimation of elements to construct maps in order to demonstrate the spatial variability of plant and soil properties. The majority of variables showed considerable variation and highly variable autocorrelation lengths.
- This study has shown that there is little or no resemblance when comparing the spatial distribution of Ca, Mg, K and P contents of lucerne with those of the soil. However, making use of a multiple regression equation, good agreement was found between the spatial distribution of measured and predicted plant K. This emphasizes the fact that the uptake of elements by plants is not solely dependent on the concentrations thereof in the extracted soil solution, but on other factors as well.

3. During the investigation of the temporal and spatial relations of plant element uptake and yield of a lucerne stand it could be concluded that:

- Although the lucerne stand contains on average adequate concentrations of plant Ca, Mg, P and K, areas of K deficiency did occur in the field during both the winter and summer seasons.
- Lower plant P and K values during summer could be due to the "dilution effect" exerted by the larger summer biomass yields.
- Weak linear correlations existed between plant elements and yield. When ignoring spatial correlations, statistically significant differences were evident when comparing nutrient status and yield between winter and summer growing seasons.

- Similarities were discernable between winter and summer spatial variations of plant Ca, Mg, P and K, with summer values either higher (Ca, Mg) or lower (P, K) than winter values.
- Statistical relationships existed between soil Mg and K and plant uptake.
- In the case of Mg, clear spatial similarities were visible between the nutrient concentration in the soil and plant uptake.
- Temporal variations in lucerne yield were observed, with the lowest and highest yields in June and September, respectively. Although there were large differences in spatial variation of lucerne yields across the harvesting incidents, a similar trough of lower yields was evident towards one end (northwestern side) of the stand for each yield map.
- A clear resemblance between spatial plant K and yield existed, probably because the deficiency in plant K was a dominant factor in causing spatial variation in yield.
- Although this study revealed spatial and temporal patterns in plant element uptake and yield of a lucerne stand at a specific location, the results illustrate some useful practical aspects relevant to site-specific management of lucerne stands. They are: (1) the temporal effect on correlation range of lucerne yield should be taken into account when deciding on time frames for soil sampling, (2) temporal lucerne yield variability should be recognized, described and manipulated when decisions are made in terms of precision agriculture, and (3) the variation in correlation ranges of the various plant elements should be considered in plant sampling patterns.

4. When examining the spatial variation of soil and plant properties and its effects on the statistical design of a field experiment the following was concluded:

- Analysis of variance of a randomized complete block design that consisted of pseudo treatments with replications revealed statistically non-significant differences among treatments for various soil and plant properties, including yield. From this the conclusion could be made that the experimental field is homogeneous enough to lay out a standard block design experiment. A spatial map of soil pH(H_2O) showed a clear structure in spatial variability. The question was posed that if the latter spatial variation had been considered, would it have had any effect on the results of this field experiment, for example, in terms of yield?

- The consequent redesign of the experiment whereby all plots were randomly allocated to treatments and replicates, led to dramatically different results: significant differences were obtained for plant and soil properties as a function of the pseudo treatments.
- From this study it is clear that spatial variability of soil and plant properties can jeopardize the results of a standard block design field experiment. However, it was found that soil pH(H_2O) correlated very well with green biomass yield. It is, therefore, recommended that field experiments should be designed to the cognizance of the spatial variation of a soil property that correlates highly with a chosen response variate.
- From the results of this study a pre-trial sampling grid of 40 m with additional short distance sampling at a few randomly selected points is recommended to quantify the chosen response variate. Hence, in the final statistical analysis to test for treatment differences, the particular soil property must be treated as a covariate. Consequent experimental results can now be interpreted with much greater confidence.

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God for guidance, perseverance and the strength to work.

APPENDIX A Soil analysis data

XCoord	YCoord	MNr	Lab	pH	Org C	P	P	Ca	K	Na	Mg	Resistance	Clay	Sand	Silt	Water retention
				(H2O)	(Walkley Black)	(Bray1)	(Ambic)	(Ammonium Acetate extract)					(Hydrometer - 3 fractions)			(-33kPa)
27.82901	-25.55235	G1	M948	8.47	1.36	9.29	19.71	6959	468	115	1464	380	46	28.18	25.82	31.88
27.82921	-25.55230	G2	M991	8.14	1.47	10.01	9.75	4865	316	92	851	460	50	21.12	28.88	33.60
27.82938	-25.55224	G3	M935	8.44	1.19	10.07	16.68	7085	346	216	1551	360	46	28.48	25.52	30.09
27.82957	-25.55219	G4	M1020	8.53	1.14	7.97	11.05	6553	239	184	1727	460	44	30.1	25.9	33.76
27.82976	-25.55213	G5	M996	8.30	1.3	19.54	12.13	5992	270	114	994	420	44	27.9	28.1	32.88
27.82996	-25.55208	G6	M1001	8.38	1.34	6.86	12.13	8657	320	158	1709	420	46	27.06	26.94	34.11
27.83015	-25.55202	G7	M946	8.44	1.22	9.84	15.38	7311	348	146	1480	340	44	31.38	24.62	32.43
27.83035	-25.55197	G8	M1018	8.50	1.36	7.77	21.88	6683	399	122	1548	460	50	25.24	24.76	37.50
27.82910	-25.55255	G9	M1052	8.38	1.17	5.75	17.52	6551	306	144	1620	420	44	37.74	18.26	25.78
27.82926	-25.55249	G10	M979	8.18	1.38	10.48	18.63	4428	308	101	902	380	42	29.14	28.86	32.57
27.82946	-25.55244	G11	M1005	8.50	1.23	7.91	11.05	6686	263	127	1592	440	44	28.02	27.98	32.52
27.82965	-25.55238	G12	M980	8.62	1.1	4.87	7.80	6490	198	194	1633	400	42	35.56	22.44	29.99
27.82985	-25.55233	G13	M958	8.47	1.14	3.34	10.18	7024	204	129	1664	380	44	31.6	24.4	30.51
27.83004	-25.55227	G14	M987	8.38	1.22	8.99	7.26	6728	247	110	995	440	42	32.92	25.08	31.73
27.83024	-25.55222	G15	M1045	8.57	1.21	4.20	14.68	6579	309	257	1547	540	46	31.2	22.8	29.02
27.83040	-25.55213	G16	M985	8.47	1.12	7.6	14.84	6123	336	118	1510	440	44	32.46	23.54	29.10
27.82915	-25.55272	G17	M921	8.64	1.06	9.77	20.15	5685	271	184	1462	380	42	36.14	21.86	25.77
27.82935	-25.55266	G18	M1013	8.12	1.46	9.77	25.13	4029	352	73	776	460	46	33.2	20.8	30.86
27.82954	-25.55260	G19	M918	8.36	1.33	9.18	16.25	6600	318	78	992	420	40	38.98	21.02	26.91
27.82974	-25.55255	G20	M937	8.64	1.12	8.11	30.54	6348	256	268	1737	380	40	38.74	21.26	29.05
27.82990	-25.55247	G21	M956	8.26	1.19	4.68	14.30	6076	254	158	1670	440	44	33.26	22.74	30.30
27.83010	-25.55244	G22	M895	8.48	1.15	7.20	7.80	6556	261	106	1455	420	44	32.12	23.88	30.23
27.83029	-25.55238	G23	M1061	8.25	1.33	7.56	11.61	7440	283	89	861	480	44	32.04	23.96	26.19
27.83049	-25.55233	G24	M1033	8.70	1.02	11.67	12.79	5712	240	279	996	400	44	37.72	18.28	27.40
27.82924	-25.55288	G25	M938	8.76	0.96	12.18	19.71	5497	267	253	1651	380	40	33.56	26.44	27.34
27.82943	-25.55283	G26	M1038	8.18	1.36	8.85	26.05	4102	245	84	713	600	40	36.42	23.58	26.07
27.82963	-25.55277	G27	M925	8.87	1.02	11.10	22.75	5607	274	520	1504	340	42	38.28	19.72	26.24
27.82979	-25.55272	G28	M1006	8.67	1.06	5.64	16.36	5345	276	349	1518	440	40	40.04	19.96	26.09
27.82999	-25.55266	G29	M992	8.42	1.23	11.81	13.22	5826	249	198	1681	360	42	36.44	21.56	30.97

27.83018	-25.55260	G30	M1059	8.30	1.29	4.13	9.59	5381	231	91	917	460	46	26.78	27.22	28.54
27.83038	-25.55255	G31	M997	8.56	1.06	5.64	9.32	6820	300	272	1917	440	46	30.6	23.4	30.69
27.83057	-25.55249	G32	M886	8.35	0.95	6.32	11.05	6512	254	118	1568	440	50	29.76	20.24	30.53
27.82929	-25.55305	G33	M962	8.40	1.08	14.12	31.62	5094	259	87	852	420	44	32.52	23.48	27.32
27.82949	-25.55299	G34	M1054	7.94	1.40	5.04	30.78	3398	247	78	643	1400	48	30.22	21.78	21.76
27.82968	-25.55294	G35	M950	8.57	1.08	14.46	25.24	4727	258	143	940	360	40	40.72	19.28	25.31
27.82988	-25.55288	G36	M903	8.69	1.05	13.67	25.78	5128	242	223	1415	440	40	42.86	17.14	21.36
27.83004	-25.55283	G37	M1007	8.58	1.08	7.16	16.47	5328	233	220	1516	440	40	38.76	21.24	26.07
27.83024	-25.55277	G38	M1028	8.47	1.24	3.29	16.47	3562	203	118	831	500	44	34.18	21.82	26.22
27.83043	-25.55272	G39	M891	8.76	1.04	8.44	25.34	5737	337	323	1718	380	46	33.2	20.8	32.45
27.83063	-25.55266	G40	M1053	8.45	0.98	6.22	12.91	5394	283	95	1481	440	44	35.78	20.22	25.99
27.82938	-25.55322	G41	M995	7.87	1.18	9.26	40.29	3784	281	89	680	1600	40	39.2	20.8	24.11
27.82957	-25.55316	G42	M1026	7.68	1.42	9.67	45.70	2445	262	75	597	1600	40	41.92	18.08	21.49
27.82976	-25.55310	G43	M883	8.44	1.23	20.47	41.91	4092	359	167	773	1500	40	40	20	26.72
27.82996	-25.55305	G44	M1043	8.56	1.08	4.97	29.36	4593	240	154	797	440	40	40.12	19.88	23.55
27.83015	-25.55299	G45	M951	8.38	1.22	13.90	26.10	5492	349	131	1433	380	42	36.9	21.1	27.23
27.83032	-25.55294	G46	M972	8.46	1.14	9.82	65.19	6031	357	198	1683	400	40	37.36	22.64	26.52
27.83051	-25.55288	G47	M983	8.95	0.88	7.20	15.60	5616	305	531	1700	360	42	38.82	19.18	28.07
27.83071	-25.55283	G48	M1029	8.50	0.98	8.62	15.04	5392	221	162	1518	480	42	38.12	19.88	24.72
27.82946	-25.55338	G49	M893	7.67	1.24	22.58	43.43	2234	297	76	641	480	40	40.1	19.9	21.04
27.82965	-25.55333	G50	M988	7.53	1.42	4.70	44.62	1985	206	56	515	1600	40	42.92	17.08	23.54
27.82985	-25.55327	G51	M913	7.81	1.38	22.04	32.27	2495	226	62	594	1600	40	45.02	14.98	21.44
27.83001	-25.55322	G52	M982	8.14	1.16	10.68	29.68	2710	170	128	728	380	40	40.04	19.96	21.26
27.83021	-25.55316	G53	M943	8.56	1.08	12.92	24.59	4046	214	181	891	420	50	35.02	14.98	25.67
27.83040	-25.55310	G54	M909	8.64	1.08	8.45	18.63	5302	224	202	1437	400	40	41.08	18.92	23.69
27.83057	-25.55305	G55	M1022	8.74	1	6.22	20.36	4503	258	198	986	460	40	40.2	19.8	24.17
27.83076	-25.55299	G56	M1055	8.76	0.95	15.32	17.05	5407	265	371	1655	380	40	35.18	24.82	25.86
27.82951	-25.55355	G57	M1016	7.68	1.12	6.79	25.67	1870.	154	60	462	1400	46	41.9	12.1	21.21
27.82971	-25.55349	G58	M926	7.65	1.03	8.41	21.99	1953	123	65	532	1600	42	37.68	20.32	21.94
27.82990	-25.55344	G59	M878	7.68	1.18	11.96	32.49	2476	180	91	728	1500	40	42.26	17.74	25.30
27.83010	-25.55338	G60	M959	7.67	1.32	10.29	28.05	3344	143	62	599	1400	44	36.68	19.32	24.28
27.83029	-25.55333	G61	M1024	7.74	1.32	6.22	26.86	2487	177	74	601	1600	40	38.28	21.72	23.25
27.83049	-25.55327	G62	M1002	8.44	1.09	6.02	14.73	3976	198	192	766	440	40	41.78	18.22	24.41
27.83065	-25.55322	G63	M919	8.56	1.06	12.74	19.82	4345	234	133	964	380	42	33.3	24.7	28.51

27.83085	-25.55316	G64	M957	8.53	1.16	10.44	25.34	5364	284	268	1575	500	44	36.74	19.26	26.59
27.82960	-25.55372	G65	M970	7.68	1.08	11.06	35.41	3100	166	80	525	1600	40	45.28	14.72	22.64
27.82979	-25.55366	G66	M875	7.61	1.16	15.28	38.23	1565	111	64	399	1600	38	47.2	14.8	20.68
27.82999	-25.55360	G67	M927	7.58	1.1	11.81	29.46	1854	132	62	440	1600	40	41.86	18.14	19.13
27.83015	-25.55355	G68	M954	7.66	1.17	8.08	16.68	2068	106	70	581	440	40	41.28	18.72	20.83
27.83035	-25.55349	G69	M876	7.57	1.33	17.62	39.20	1737	119	64	411	1600	42	40.22	17.78	27.99
27.83054	-25.55344	G70	M928	7.73	1.26	20.28	42.02	3730	154	83	641	1600	44	37.9	18.1	25.20
27.83074	-25.55338	G71	M911	7.85	1.16	14.38	26.21	2678	169	92	727	440	44	35.16	20.84	25.70
27.83093	-25.55333	G72	M989	8.08	1.19	17.58	27.29	2964	192	125	884	420	40	41.68	18.32	26.10
27.83017	-25.55201	G7.1	M955	8.64	1.08	6.21	9.43	7135	227	316	1558	400	46	30.38	23.62	34.83
27.83019	-25.55200	G7.2	M907	8.88	1.12	8.08	15.27	6176	249	517	1522	340	46	29.7	24.3	32.01
27.83022	-25.55200	G7.3	M905	8.74	1.1	10.77	16.47	6421	298	459	1592	360	46	28.96	25.04	33.70
27.83016	-25.55204	G7.4	M917	8.69	1.06	7.34	12.13	7916	226	202	1512	380	42	32.36	25.64	29.87
27.83018	-25.55203	G7.5	M922	8.67	1.08	9.92	13.22	7981	272	243	1831	400	46	25.62	28.38	30.81
27.83020	-25.55203	G7.6	M1019	8.67	1.26	9.60	45.70	5164	270	254	964	440	44	29.8	26.2	31.90
27.83023	-25.55202	G7.7	M923	8.79	1.13	8.33	15.27	6400	285	341	1649	420	44	32.62	23.38	31.82
27.83017	-25.55206	G7.8	M1049	8.78	1.07	8.75	12.35	6083	184	325	893	400	40	33.8	26.2	27.76
27.83019	-25.55206	G7.9	M1060	8.65	1.12	4.30	12.13	5777	239	200	946	440	44	31.76	24.24	26.36
27.83021	-25.55205	G7.10	M1010	8.80	1.13	7.50	14.30	6088	257	370	971	380	40	28.74	31.26	32.22
27.83024	-25.55205	G7.11	M894	8.94	1.10	11.03	17.33	6432	283	462	1591	380	46	27.3	26.7	32.61
27.83018	-25.55209	G7.12	M1008	8.91	0.95	7.03	17.55	5713	175	473	864	460	40	34.1	25.9	29.03
27.83020	-25.55208	G7.13	M872	8.81	1.01	6.57	12.13	6829	244	487	1761	1600	46	32.1	21.9	31.51
27.83022	-25.55207	G7.14	M897	8.94	0.99	10.99	21.67	6116	255	442	1456	400	42	29.5	28.5	34.64
27.83025	-25.55207	G7.15	M981	8.85	1.03	8.65	14.56	6894	259	509	1595	420	42	32.4	25.6	32.85
27.82928	-25.55248	G10.1	M1014	8.06	1.48	13.07	17.55	5035	280	226	893	440	48	23.9	28.1	34.24
27.82930	-25.55247	G10.2	M904	8.26	1.3	9.11	13.43	3737	175	90	811	420	50	23.02	26.98	33.94
27.82933	-25.55247	G10.3	M1056	8.20	1.40	7.03	9.36	5304	249	102	850	440	48	23.94	28.06	31.17
27.82927	-25.55251	G10.4	M977	8.33	1.27	8.45	14.52	4644	250	108	883	420	42	26.52	31.48	30.61
27.82929	-25.55251	G10.5	M1037	8.17	1.37	3.46	15.87	5153	224	89	746	480	44	28.16	27.84	28.78
27.82931	-25.55250	G10.6	M994	8.16	1.4	10.75	15.49	5251	306	92	789	500	40	28.24	31.76	31.54
27.82934	-25.55249	G10.7	M1015	8.14	1.38	9.94	12.13	4575	271	97	830	480	40	24.54	35.46	31.50
27.82928	-25.55253	G10.8	M1035	8.34	1.29	8.41	16.81	5046	201	87	740	480	46	27.1	26.9	28.54
27.82930	-25.55253	G10.9	M933	8.37	1.29	9.66	14.84	4781	221	105	892	380	46	25.76	28.24	31.73
27.82932	-25.55252	G10.10	M932	8.26	1.31	9.18	11.27	4747	258	105	898	420	46	26.98	27.02	31.31

27.82935	-25.55252	G10.11	M961	8.30	1.33	9.81	16.03	4346	222	106	875	400	46	22.62	31.38	30.50
27.82929	-25.55256	G10.12	M1030	8.37	1.26	7.10	8.67	5290	245	109	862	480	46	28.28	25.72	27.01
27.82931	-25.55255	G10.13	M912	8.35	1.26	9.36	12.13	4809	229	109	869	440	46	27.46	26.54	31.67
27.82933	-25.55254	G10.14	M908	8.17	1.35	10.44	15.49	4816	267	111	917	480	42	25.96	32.04	31.67
27.82936	-25.55254	G10.15	M915	8.24	1.3	8.52	13.00	5468	239	93	902	1600	44	25.46	30.54	30.30
27.82992	-25.55246	G21.1	M968	8.64	0.98	3.19	5.64	6110	153	188	1749	420	48	30.38	21.62	29.85
27.82994	-25.55245	G21.2	M944	8.67	0.93	4.46	8.89	6645	125	172	1735	380	50	30.44	19.56	30.31
27.82997	-25.55245	G21.3	M973	8.54	1.07	3.37	8.89	6621	190	224	1637	380	44	32.84	23.16	31.41
27.82991	-25.55249	G21.4	M931	8.60	1.04	5.22	5.75	5227	185	133	1585	400	46	30.94	23.06	28.14
27.82993	-25.55248	G21.5	M880	8.57	1.01	4.93	6.07	5975	200	183	1866	1600	48	32.78	19.22	33.23
27.82995	-25.55248	G21.6	M1027	8.42	1.07	19.06	5.10	6185	219	167	1750	460	44	30.42	25.58	30.73
27.82998	-25.55247	G21.7	M874	8.53	1.07	4.86	8.34	5938	194	137	1543	1400	46	32.74	21.26	29.09
27.82992	-25.55251	G21.8	M934	8.85	1.01	4.21	6.18	5428	141	157	1584	420	46	29.56	24.44	29.70
27.82994	-25.55251	G21.9	M949	8.62	1.03	5.30	6.72	5574	147	180	1613	380	44	29.94	26.06	25.42
27.82996	-25.55250	G21.10	M1044	8.48	1.05	12.18	6.75	5973	170	129	1657	480	40	34.18	25.82	29.07
27.82999	-25.55250	G21.11	M978	8.56	1.04	4.47	6.29	6055	156	125	1659	400	44	29.2	26.8	31.69
27.82993	-25.55254	G21.12	M902	8.65	0.94	5.44	7.80	5283	158	152	1673	400	46	30.26	23.74	26.81
27.82995	-25.55253	G21.13	M929	8.56	1.01	5.04	8.89	5796	187	147	1679	380	46	29.7	24.3	29.73
27.82997	-25.55252	G21.14	M965	8.68	1.03	3.95	7.80	5648	133	136	1553	420	46	31.56	22.44	31.08
27.83000	-25.55252	G21.15	M952	8.49	1.07	4.35	29.57	6124	214	167	1760	440	42	34.42	23.58	30.73
27.82931	-25.55304	G33.1	M887	8.46	1.08	11.58	16.47	3758	230	86	797	480	40	36.66	23.34	27.00
27.82933	-25.55303	G33.2	M986	8.30	1.14	9.16	21.66	4867	209	96	837	460	40	34.16	25.84	26.19
27.82936	-25.55303	G33.3	M877	8.40	1.07	10.92	16.47	2705	137	74	633	1500	42	34.26	23.74	26.64
27.82930	-25.55307	G33.4	M964	8.37	1.01	12.18	22.10	4274	205	75	700	440	40	41.64	18.36	23.10
27.82932	-25.55306	G33.5	M953	8.21	1.05	9.14	16.47	4212	187	91	758	1400	40	37.04	22.96	26.21
27.82934	-25.55306	G33.6	M1057	8.18	1.17	5.54	18.47	3766	143	71	663	480	40	34.3	25.7	16.39
27.82937	-25.55305	G33.7	M1025	8.12	1.18	9.97	27.83	3116	168	91	699	500	40	33.8	26.2	24.39
27.82931	-25.55309	G33.8	M884	8.16	0.95	11.88	19.93	2873	192	73	723	1600	44	34.1	21.9	26.32
27.82933	-25.55309	G33.9	M1034	8.10	1.18	5.51	22.26	3329	144	72	672	500	40	37.24	22.76	24.59
27.82935	-25.55308	G33.10	M1003	8.12	1.19	11.13	16.79	4105	150	82	731	460	40	37.52	22.48	25.67
27.82938	-25.55308	G33.11	M969	8.07	1.17	8.75	19.71	3934	152	88	741	480	42	35.74	22.26	26.42
27.82932	-25.55312	G33.12	M1048	8.60	1.09	6.86	22.02	3542	149	87	675	460	40	40.92	19.08	20.75
27.82934	-25.55311	G33.13	M1040	8.14	1.07	4.84	21.78	4104	158	95	827	640	40	41.7	18.3	23.19
27.82936	-25.55310	G33.14	M940	8.14	1.2	13.34	21.12	2755	151	73	712	560	42	41.06	16.94	23.19

27.82939	-25.55310	G33.15	M879	8.15	1.11	11.81	21.88	2238	116	73	643	1600	44	32.38	23.62	22.83
27.83034	-25.55293	G46.1	M1058	8.56	1.06	9.19	17.17	4772	215	186	944	380	42	36.84	21.16	22.47
27.83036	-25.55293	G46.2	M906	8.87	0.89	7.05	13.22	4777	162	279	1445	360	42	37.62	20.38	27.16
27.83039	-25.55292	G46.3	M1023	8.82	0.90	8.38	13.22	4967	171	300	1486	440	42	36.6	21.4	26.07
27.83033	-25.55296	G46.4	M1011	8.72	0.97	8.41	9.43	5380	217	332	1606	440	40	39.22	20.78	27.56
27.83035	-25.55296	G46.5	M998	8.60	1.05	4.16	13.22	4257	246	255	977	420	44	31.62	24.38	27.60
27.83037	-25.55295	G46.6	M888	8.74	0.99	8.15	27.29	5166	238	310	1555	420	42	38.1	19.9	26.99
27.83040	-25.55294	G46.7	M1000	8.94	0.92	7.20	9.97	6031	217	442	1732	440	40	37.38	22.62	26.56
27.83034	-25.55298	G46.8	M939	8.85	0.93	7.31	9.97	5578	163	322	1679	380	40	36.96	23.04	25.40
27.83036	-25.55298	G46.9	M1009	8.65	1.02	7.53	15.38	5231	211	341	1491	440	44	43.82	12.18	23.41
27.83038	-25.55297	G46.10	M971	8.78	0.98	6.02	15.38	5354	160	305	1496	440	44	36.8	19.2	26.32
27.83041	-25.55297	G46.11	M945	9.02	0.92	8.33	12.68	4993	185	345	1420	340	42	37.68	20.32	27.62
27.83035	-25.55301	G46.12	M898	8.87	0.89	9.73	14.52	5102	203	307	1496	360	40	39.66	20.34	25.34
27.83037	-25.55300	G46.13	M916	8.79	0.96	9.25	15.00	4968	254	396	1436	1400	40	41.5	18.5	28.32
27.83039	-25.55299	G46.14	M892	8.84	1.00	9.77	14.52	5507	283	325	1694	400	42	34.76	23.24	30.12
27.83042	-25.55299	G46.15	M942	8.74	0.98	7.60	12.13	5806	213	339	1642	380	44	36.5	19.5	26.75
27.83012	-25.55337	G60.1	M1046	7.64	1.35	5.21	25.81	2903	125	81	610	1800	40	40.86	19.14	23.08
27.83014	-25.55336	G60.2	M993	7.61	1.38	5.64	27.29	2209	137	71	544	1600	40	38.56	21.44	21.99
27.83017	-25.55336	G60.3	M881	7.68	1.20	8.22	49.60	2095	123	73	581	1600	40	42.76	17.24	23.60
27.83011	-25.55340	G60.4	M1017	7.62	1.21	10.35	18.74	1881	94	66	467	1600	46	33.68	20.32	25.82
27.83013	-25.55339	G60.5	M1004	7.49	1.23	8.72	21.23	2483	139	84	604	1400	40	41.84	18.16	20.50
27.83015	-25.55339	G60.6	M966	7.56	1.38	9.59	26.21	2167	169	81	557	1600	40	41.24	18.76	22.49
27.83018	-25.55338	G60.7	M975	7.64	1.21	8.72	25.02	2995	131	68	546	1600	42	39.36	18.64	22.08
27.83012	-25.55342	G60.8	M967	7.69	1.21	10.47	28.38	1977	159	69	547	1400	44	35.4	20.6	23.77
27.83014	-25.55342	G60.9	M910	7.67	1.25	9.36	22.96	3084	150	77	587	460	44	37.96	18.04	22.80
27.83016	-25.55341	G60.10	M984	7.6	1.27	12.32	24.04	3087	186	74	547	1600	40	43.1	16.9	22.58
27.83019	-25.55341	G60.11	M889	7.68	1.19	12.11	25.67	2119	198	72	567	1600	42	36.68	21.32	21.07
27.83013	-25.55345	G60.12	M930	7.64	1.27	14.83	26.97	3233	160	70	588	1600	46	35.6	18.4	23.36
27.83015	-25.55344	G60.13	M990	7.67	1.26	12.90	27.08	3177	134	75	523	1600	40	41.36	18.64	21.94
27.83017	-25.55343	G60.14	M1032	7.62	1.29	8.35	24.91	2469	168	83	563	1600	42	40.28	17.72	21.00
27.83020	-25.55343	G60.15	M974	7.84	1.14	8.52	26.75	3096	132	63	545	1600	40	41.98	18.02	22.28

APPENDIX B Lucerne yield data

MNr.	Yield - June 2001		Yield - August 2001		Yield - September 2001		Yield - October 2001		Yield - November 2001		Yield - February 2002	
	g/sample	t/ha	g/sample	t/ha	g/sample	t/ha	g/sample	t/ha	g/sample	t/ha	g/sample	t/ha
G1	154.28	4.29	268.5	7.46	421.64	11.71	442	12.28	512.08	14.22	350.51	9.74
G2	201.24	5.59	225.5	6.26	404.82	11.25	316	8.78	233.23	6.48	508.26	14.12
G3	211.04	5.86	264.4	7.34	319.20	8.87	343	9.53	201.18	5.59	133.88	3.72
G4	121.79	3.38	175.3	4.87	253.00	7.03	339	9.42	169.73	4.71	148.46	4.12
G5	129.34	3.59	262.6	7.29	294.20	8.17	326	9.06	232.96	6.47	304.35	8.45
G6	302.54	8.40	525.1	14.59	606.90	16.86	485	13.47	340.93	9.47	434.52	12.07
G7	204.81	5.69	364.6	10.13	458.24	12.73	377	10.47	247.59	6.88	409.32	11.37
G8	57.28	1.59	174.0	4.83	118.90	3.30	122	3.39	264.05	7.33	513.74	14.27
G9	140.11	3.89	378.2	10.51	380.31	10.56	280	7.78	410.24	11.40	282.76	7.85
G10	321.69	8.94	515.3	14.31	582.72	16.19	648	18.00	549.38	15.26	464.18	12.89
G11	139.62	3.88	306.1	8.50	310.60	8.63	352	9.78	353.67	9.82	355.68	9.88
G12	100.97	2.80	284.5	7.90	200.80	5.58	221	6.14	232.69	6.46	221.50	6.15
G13	250.02	6.95	441.1	12.25	423.20	11.76	443	12.31	326.10	9.06	347.23	9.65
G14	202.51	5.63	306.3	8.51	356.90	9.91	457	12.69	357.53	9.93	435.48	12.10
G15	136.41	3.79	296.0	8.22	287.40	7.98	308	8.56	247.31	6.87	169.30	4.70
G16	129.85	3.61	223.8	6.22	449.30	12.48	444	12.33	293.36	8.15	504.96	14.03
G17	123.37	3.43	255.3	7.09	257.00	7.14	318	8.83	218.67	6.07	117.93	3.28
G18	329.62	9.16	412.7	11.46	572.33	15.90	407	11.31	356.13	9.89	380.18	10.56
G19	308.26	8.56	344.1	9.56	485.94	13.50	374	10.39	333.40	9.26	318.05	8.83
G20	114.41	3.18	191.4	5.32	296.82	8.25	214	5.94	163.71	4.55	215.50	5.99
G21	194.67	5.41	250.0	6.94	335.50	9.32	384	10.67	323.19	8.98	154.93	4.30
G22	217.93	6.05	263.2	7.31	392.36	10.90	392	10.89	316.39	8.79	379.95	10.55
G23	272.39	7.57	354.8	9.86	510.68	14.19	366	10.17	363.45	10.10	394.62	10.96
G24	67.18	1.87	268.0	7.44	232.14	6.45	250	6.94	234.10	6.50	104.55	2.90
G25	110.69	3.07	342.7	9.52	325.00	9.03	264	7.33	266.32	7.40	117.80	3.27
G26	274.63	7.63	395.0	10.97	619.00	17.19	261	7.25	231.94	6.44	401.58	11.16
G27	127.80	3.55	368.7	10.24	343.00	9.53	309	8.58	281.92	7.83	212.96	5.92
G28	146.25	4.06	275.7	7.66	203.00	5.64	223	6.19	225.69	6.27	210.87	5.86
G29	150.65	4.18	325.8	9.05	231.00	6.42	343	9.53	268.75	7.47	161.04	4.47
G30	188.04	5.22	301.9	8.39	424.00	11.78	331	9.19	219.68	6.10	386.16	10.73

G31	135.63	3.77	326.2	9.06	443.24	12.31	283	7.86	235.58	6.54	186.51	5.18
G32	131.02	3.64	229.8	6.38	375.57	10.43	221	6.14	300.70	8.35	378.02	10.50
G33	227.23	6.31	338.9	9.41	431.00	11.97	568	15.78	401.78	11.16	290.01	8.06
G34	311.11	8.64	563.7	15.66	752.00	20.89	551	15.31	412.42	11.46	261.28	7.26
G35	172.76	4.80	363.5	10.10	280.54	7.79	318	8.83	184.43	5.12	270.55	7.52
G36	127.82	3.55	376.8	10.47	297.18	8.26	293	8.14	221.83	6.16	260.80	7.24
G37	134.96	3.75	323.1	8.98	255.00	7.08	260	7.22	217.73	6.05	176.06	4.89
G38	164.62	4.57	328.1	9.11	426.72	11.85	480	13.33	268.20	7.45	248.03	6.89
G39	164.87	4.58	343.1	9.53	559.28	15.54	393	10.92	240.65	6.68	231.81	6.44
G40	73.52	2.04	178.9	4.97	170.75	4.74	175	4.86	116.00	3.22	238.93	6.64
G41	195.33	5.43	366.2	10.17	427.00	11.86	401	11.14	342.48	9.51	372.81	10.36
G42	375.95	10.44	483.7	13.44	506.00	14.06	424	11.78	382.10	10.61	548.70	15.24
G43	214.77	5.97	346.3	9.62	517.00	14.36	295	8.19	267.78	7.44	360.91	10.03
G44	176.31	4.90	291.2	8.09	303.00	8.42	265	7.36	223.80	6.22	305.18	8.48
G45	187.53	5.21	301.0	8.36	316.00	8.78	314	8.72	313.38	8.71	230.35	6.40
G46	220.52	6.13	306.6	8.52	254.00	7.06	346	9.61	295.09	8.20	323.01	8.97
G47	61.53	1.71	108.1	3.00	143.00	3.97	210	5.83	98.33	2.73	245.71	6.83
G48	125.28	3.48	227.5	6.32	232.00	6.44	190	5.28	184.34	5.12	305.83	8.50
G49	238.06	6.61	471.2	13.09	660.00	18.33	381	10.58	194.63	5.41	512.40	14.23
G50	279.37	7.76	429.9	11.94	753.00	20.92	608	16.89	309.32	8.59	504.16	14.00
G51	312.86	8.69	378.4	10.51	705.00	19.58	508	14.11	389.61	10.82	593.90	16.50
G52	215.29	5.98	334.8	9.30	618.00	17.17	414	11.50	352.96	9.80	566.88	15.75
G53	208.95	5.80	224.7	6.24	321.00	8.92	295	8.19	261.93	7.28	145.79	4.05
G54	185.16	5.14	294.4	8.18	506.00	14.06	330	9.17	279.15	7.75	204.78	5.69
G55	153.29	4.26	253.6	7.04	400.00	11.11	272	7.56	198.87	5.52	438.20	12.17
G56	141.95	3.94	231.3	6.43	282.00	7.83	176	4.89	91.37	2.54	478.50	13.29
G57	338.67	9.41	498.7	13.85	555.00	15.42	447	12.42	309.39	8.59	490.18	13.62
G58	289.92	8.05	595.8	16.55	665.00	18.47	427	11.86	296.30	8.23	442.58	12.29
G59	356.29	9.90	529.6	14.71	619.00	17.19	431	11.97	314.39	8.73	445.94	12.39
G60	355.69	9.88	523.7	14.55	593.00	16.47	351	9.75	362.71	10.08	391.96	10.89
G61	299.69	8.32	463.0	12.86	702.00	19.50	502	13.94	272.39	7.57	565.34	15.70
G62	323.90	9.00	655.9	18.22	692.00	19.22	374	10.39	295.19	8.20	103.52	2.88
G63	256.49	7.12	345.5	9.60	451.00	12.53	245	6.81	194.83	5.41	186.44	5.18
G64	184.80	5.13	429.4	11.93	330.00	9.17	180	5.00	91.80	2.55	184.84	5.13

G65	237.44	6.60	437.2	12.14	476.00	13.22	321	8.92	106.06	2.95	596.50	16.57
G66	183.56	5.10	335.0	9.31	493.00	13.69	421	11.69	267.25	7.42	395.71	10.99
G67	273.29	7.59	348.7	9.69	408.00	11.33	396	11.00	197.57	5.49	318.25	8.84
G68	220.42	6.12	416.0	11.56	411.00	11.42	457	12.69	196.42	5.46	417.66	11.60
G69	351.29	9.76	419.3	11.65	402.00	11.17	451	12.53	339.70	9.44	510.62	14.18
G70	240.29	6.67	341.0	9.47	358.00	9.94	292	8.11	224.26	6.23	458.30	12.73
G71	262.22	7.28	412.6	11.46	479.00	13.31	436	12.11	255.12	7.09	415.78	11.55
G72	209.22	5.81	233.4	6.48	163.00	4.53	255	7.08	216.87	6.02	186.99	5.19
G7.1	166.57	4.63	282.2	7.84	356.00	9.89	390	10.83	321.64	8.93	237.82	6.61
G7.2	82.60	2.29	142.5	3.96	217.00	6.03	217	6.03	134.58	3.74	163.07	4.53
G7.3	98.83	2.75	245.3	6.81	251.00	6.97	276	7.67	168.03	4.67	216.40	6.01
G7.4	145.92	4.05	208.5	5.79	360.00	10.00	356	9.89	325.34	9.04	167.46	4.65
G7.5	141.70	3.94	226.3	6.29	375.00	10.42	460	12.78	388.84	10.80	299.21	8.31
G7.6	125.73	3.49	212.0	5.89	258.00	7.17	252	7.00	204.19	5.67	190.61	5.29
G7.7	129.58	3.60	164.6	4.57	285.00	7.92	308	8.56	223.41	6.21	172.23	4.78
G7.8	118.01	3.28	187.5	5.21	170.00	4.72	253	7.03	146.36	4.07	74.67	2.07
G7.9	150.12	4.17	218.6	6.07	352.00	9.78	394	10.94	296.74	8.24	123.51	3.43
G7.10	132.56	3.68	239.5	6.65	202.00	5.61	323	8.97	255.67	7.10	122.24	3.40
G7.11	123.29	3.42	422.8	11.74	279.00	7.75	298	8.28	212.39	5.90	246.20	6.84
G7.12	76.10	2.11	230.7	6.41	190.00	5.28	229	6.36	173.52	4.82	90.46	2.51
G7.13	168.44	4.68	297.9	8.28	362.00	10.06	404	11.22	334.55	9.29	181.81	5.05
G7.14	102.54	2.85	213.3	5.93	163.00	4.53	284	7.89	196.62	5.46	175.41	4.87
G7.15	95.60	2.66	259.0	7.19	239.00	6.64	294	8.17	195.11	5.42	333.18	9.26
G10.1	237.51	6.60	482.1	13.39	540.00	15.00	536	14.89	464.64	12.91	424.78	11.80
G10.2	277.92	7.72	391.9	10.89	561.00	15.58	490	13.61	369.66	10.27	343.34	9.54
G10.3	284.37	7.90	481.3	13.37	733.00	20.36	585	16.25	499.68	13.88	417.70	11.60
G10.4	209.88	5.83	323.1	8.98	395.00	10.97	569	15.81	402.00	11.17	609.90	16.94
G10.5	160.43	4.46	243.8	6.77	486.00	13.50	464	12.89	351.14	9.75	536.04	14.89
G10.6	190.68	5.30	279.3	7.76	546.00	15.17	562	15.61	410.64	11.41	512.06	14.22
G10.7	226.11	6.28	386.4	10.73	706.00	19.61	546	15.17	501.56	13.93	442.82	12.30
G10.8	310.31	8.62	500.4	13.90	762.00	21.17	446	12.39	575.64	15.99	441.74	12.27
G10.9	236.26	6.56	309.1	8.59	707.00	19.64	440	12.22	510.88	14.19	549.84	15.27
G10.10	285.68	7.94	537.8	14.94	721.00	20.03	551	15.31	474.40	13.18	406.62	11.30
G10.11	225.08	6.25	385.0	10.69	652.00	18.11	436	12.11	384.66	10.69	603.80	16.77

G10.12	295.20	8.20	362.7	10.08	722.00	20.06	598	16.61	553.08	15.36	446.04	12.39
G10.13	283.04	7.86	310.4	8.62	548.00	15.22	400	11.11	789.02	21.92	464.30	12.90
G10.14	269.27	7.48	357.8	9.94	646.00	17.94	592	16.44	548.98	15.25	476.46	13.24
G10.15	227.18	6.31	320.3	8.90	807.00	22.42	428	11.89	451.46	12.54	423.88	11.77
G21.1	190.67	5.30	303.5	8.43	434.00	12.06	470	13.06	339.49	9.43	293.56	8.15
G21.2	222.53	6.18	263.9	7.33	261.00	7.25	448	12.44	300.96	8.36	274.49	7.62
G21.3	169.85	4.72	188.9	5.25	161.00	4.47	313	8.69	243.83	6.77	165.66	4.60
G21.4	183.36	5.09	274.2	7.62	453.00	12.58	600	16.67	267.17	7.42	331.27	9.20
G21.5	189.77	5.27	308.2	8.56	321.00	8.92	444	12.33	263.57	7.32	294.75	8.19
G21.6	185.87	5.16	280.6	7.79	249.00	6.92	394	10.94	325.93	9.05	342.89	9.52
G21.7	127.68	3.55	402.1	11.17	250.00	6.94	370	10.28	370.44	10.29	273.18	7.59
G21.8	179.84	5.00	313.2	8.70	286.00	7.94	285	7.92	284.61	7.91	313.09	8.70
G21.9	158.83	4.41	417.3	11.59	272.00	7.56	295	8.19	321.16	8.92	239.88	6.66
G21.10	190.49	5.29	388.6	10.79	433.00	12.03	518	14.39	409.96	11.39	471.36	13.09
G21.11	210.46	5.85	338.5	9.40	434.00	12.06	457	12.69	360.08	10.00	258.37	7.18
G21.12	201.26	5.59	320.9	8.91	242.00	6.72	176	4.89	277.48	7.71	319.36	8.87
G21.13	227.52	6.32	371.6	10.32	348.00	9.67	302	8.39	412.00	11.44	261.06	7.25
G21.14	250.46	6.96	338.0	9.39	376.00	10.44	345	9.58	350.17	9.73	414.46	11.51
G21.15	186.20	5.17	276.3	7.68	306.00	8.50	319	8.86	321.60	8.93	306.89	8.52
G33.1	242.90	6.75	288.1	8.00	453.00	12.58	460	12.78	309.70	8.60	304.06	8.45
G33.2	229.96	6.39	340.8	9.47	404.00	11.22	512	14.22	305.51	8.49	219.10	6.09
G33.3	213.18	5.92	291.2	8.09	425.00	11.81	263	7.31	269.30	7.48	336.39	9.34
G33.4	212.39	5.90	422.9	11.75	384.00	10.67	478	13.28	359.00	9.97	376.53	10.46
G33.5	183.19	5.09	301.9	8.39	397.00	11.03	420	11.67	403.72	11.21	381.30	10.59
G33.6	197.49	5.49	404.1	11.23	388.00	10.78	431	11.97	378.50	10.51	364.55	10.13
G33.7	152.44	4.23	355.1	9.86	222.00	6.17	331	9.19	286.57	7.96	306.01	8.50
G33.8	204.53	5.68	376.5	10.46	415.00	11.53	406	11.28	286.85	7.97	424.50	11.79
G33.9	258.31	7.18	313.9	8.72	315.00	8.75	446	12.39	401.50	11.15	360.07	10.00
G33.10	264.08	7.34	443.2	12.31	493.00	13.69	504	14.00	470.38	13.07	264.60	7.35
G33.11	244.63	6.80	356.1	9.89	379.00	10.53	390	10.83	395.15	10.98	362.77	10.08
G33.12	296.25	8.23	389.7	10.83	513.00	14.25	433	12.03	365.92	10.16	384.97	10.69
G33.13	257.23	7.15	354.5	9.85	318.00	8.83	418	11.61	335.16	9.31	375.50	10.43
G33.14	275.34	7.65	390.7	10.85	402.00	11.17	421	11.69	354.06	9.84	357.80	9.94
G33.15	199.13	5.53	276.9	7.69	243.00	6.75	319	8.86	401.36	11.15	351.04	9.75

G46.1	226.74	6.30	344.5	9.57	301.00	8.36	194	5.39	221.34	6.15	489.76	13.60
G46.2	133.95	3.72	291.1	8.09	358.00	9.94	241	6.69	286.80	7.97	390.14	10.84
G46.3	149.97	4.17	319.3	8.87	262.00	7.28	231	6.42	267.83	7.44	446.44	12.40
G46.4	162.88	4.52	360.5	10.01			403	11.19	330.14	9.17	454.06	12.61
G46.5	167.77	4.66	300.5	8.35	482.00	13.39	321	8.92	269.26	7.48	415.48	11.54
G46.6	201.45	5.60	300.0	8.33	320.00	8.89	375	10.42	340.63	9.46	345.82	9.61
G46.7	115.78	3.22	263.4	7.32	269.00	7.47	221	6.14	219.58	6.10	349.88	9.72
G46.8	162.96	4.53	350.6	9.74			360	10.00	354.22	9.84	451.60	12.54
G46.9	154.31	4.29	330.9	9.19	540.00	15.00	413	11.47	329.01	9.14	385.60	10.71
G46.10	157.69	4.38	382.4	10.62	435.00	12.08	383	10.64	299.65	8.32	456.90	12.69
G46.11	137.53	3.82	265.1	7.36			248	6.89	234.52	6.51	477.02	13.25
G46.12	150.66	4.19	334.1	9.28			297	8.25			451.14	12.53
G46.13	150.10	4.17	309.3	8.59			298	8.28	305.69	8.49	423.44	11.76
G46.14	177.91	4.94	399.7	11.10			359	9.97	270.40	7.51	334.09	9.28
G46.15	139.30	3.87	338.3	9.40			323	8.97	247.27	6.87	305.99	8.50
G60.1	333.77	9.27	425.8	11.83	676.00	18.78	398	11.06	384.82	10.69	483.02	13.42
G60.2	346.70	9.63	554.1	15.39	677.00	18.81	522	14.50	468.70	13.02	396.44	11.01
G60.3	313.30	8.70	502.1	13.95	653.00	18.14	419	11.64	420.48	11.68	484.54	13.46
G60.4	168.08	4.67	323.6	8.99	643.00	17.86	328	9.11	303.45	8.43	310.74	8.63
G60.5	351.10	9.75	501.6	13.93	648.00	18.00	391	10.86	471.00	13.08	443.62	12.32
G60.6	323.88	9.00	416.1	11.56	560.00	15.56	412	11.44	459.12	12.75	529.20	14.70
G60.7	315.15	8.75	411.2	11.42	645.00	17.92	407	11.31	475.30	13.20	527.22	14.65
G60.8	291.76	8.10	496.0	13.78			459	12.75	445.82	12.38	479.06	13.31
G60.9	385.80	10.72	507.2	14.09			496	13.78	449.62	12.49	351.73	9.77
G60.10	254.18	7.06	403.0	11.19			406	11.28	352.21	9.78	380.56	10.57
G60.11	312.35	8.68	618.9	17.19			501	13.92	519.40	14.43	468.30	13.01
G60.12	162.43	4.51	474.2	13.17			353	9.81	377.93	10.50	343.31	9.54
G60.13	266.04	7.39	482.9	13.41			304	8.44	226.15	6.28	457.80	12.72
G60.14	185.17	5.14	350.8	9.74			381	10.58	259.78	7.22	498.08	13.84
G60.15	174.80	4.86	243.3	6.76			365	10.14	563.00	15.64	417.64	11.60

APPENDIX C Plant analysis data

MNr.	June 2001				February 2002			
	%Ca	%Mg	%P	%K	%Ca	%K	%Mg	%P
G1	1.22	0.24	0.38	3.44	1.43	2.56	0.27	0.34
G2	1.57	0.28	0.36	2.54	1.73	1.73	0.29	0.15
G3	1.07	0.26	0.23	2.22	1.34	1.73	0.49	0.26
G4	1.34	0.47	0.28	1.30	1.12	1.34	0.48	0.14
G5	1.40	0.41	0.34	1.65	1.20	0.62	0.61	0.23
G6	1.28	0.32	0.30	2.45	1.43	1.06	0.44	0.13
G7	1.35	0.34	0.34	2.37	1.43	1.47	0.55	0.29
G8	1.19	0.20	0.35	3.49	1.29	2.25	0.28	0.12
G9	1.37	0.38	0.31	2.04	1.12	1.51	0.32	0.22
G10	1.63	0.31	0.35	2.81	1.38	1.42	0.31	0.20
G11	1.38	0.37	0.31	1.95	1.57	1.47	0.41	0.15
G12	1.41	0.41	0.31	1.54	1.18	0.89	0.52	0.24
G13	1.53	0.44	0.36	1.46	1.55	1.22	0.56	0.21
G14	1.50	0.27	0.36	2.03	1.41	1.33	0.38	0.27
G15	1.25	0.29	0.32	2.42	0.90	1.35	0.35	0.25
G16	1.23	0.23	0.33	3.23	1.24	2.09	0.36	0.28
G17	1.34	0.35	0.28	2.14	1.38	2.20	0.58	0.36
G18	1.65	0.33	0.34	2.39	1.72	1.99	0.37	0.13
G19	1.51	0.33	0.35	2.48	1.85	1.73	0.58	0.35
G20	1.32	0.40	0.30	1.93	1.36	1.79	0.51	0.36
G21	1.30	0.42	0.34	1.56	1.50	1.21	0.56	0.30
G22	1.52	0.40	0.37	1.66	1.62	1.41	0.57	0.33
G23	1.19	0.34	0.22	1.80	1.93	1.54	0.48	0.35
G24	1.01	0.23	0.28	2.30	1.08	2.96	0.36	0.31
G25	1.10	0.34	0.29	2.18	1.47	2.29	0.55	0.37
G26	1.75	0.40	0.27	2.35	1.67	1.13	0.46	0.17
G27		0.32	0.22	2.69	1.08	2.04	0.47	0.36
G28	1.28	0.40	0.31	1.93	1.23	1.45	0.53	0.24
G29	1.23	0.42	0.32	1.61	1.29	1.00	0.65	0.22
G30	1.31	0.35	0.30	2.43	2.40	2.48	0.80	0.48
G31	1.10	0.31	0.32	2.14	1.20	1.96	0.49	0.32
G32	1.32	0.43	0.33	1.51	1.37	1.52	0.63	0.32
G33	1.29	0.41	0.20	2.45	1.76	2.16	0.47	0.31
G34	1.25	0.31	0.24	2.01	1.24	2.20	0.44	0.32
G35	1.24	0.35	0.28	2.28	1.60	2.45	0.53	0.41
G36	1.16	0.40	0.31	1.87	1.24	1.87	0.59	0.43
G37	1.32	0.41	0.32	2.04	1.28	1.70	0.48	0.16
G38	1.28	0.31	0.28	1.99	1.34	1.43	0.44	0.19
G39	1.20	0.25	0.30	2.45	1.14	2.27	0.45	0.36
G40	1.19	0.45	0.26	2.24	1.24	1.81	0.50	0.22
G41	1.20	0.32	0.31	2.76	1.38	1.58	0.35	0.15
G42	1.25	0.30	0.32	2.67	1.03	1.88	0.30	0.17

G43	1.20	0.26	0.29	2.84	1.62	2.71	0.50	0.52
G44	1.08	0.32	0.29	2.27	0.92	1.49	0.34	0.20
G45	1.04	0.31	0.30	2.43	1.80	2.43	0.52	0.29
G46	1.09	0.30	0.30	2.32	1.41	2.21	0.44	0.28
G47	0.92	0.25	0.29	2.71	0.86	1.91	0.34	0.20
G48	0.98	0.38	0.26	1.63	1.28	1.60	0.54	0.36
G49	1.47	0.32	0.30	2.25	1.38	2.32	0.40	0.35
G50	1.25	0.27	0.32	2.42	1.69	1.84	0.42	0.31
G51	1.31	0.32	0.34	2.44	1.67	2.24	0.47	0.36
G52	1.12	0.34	0.31	2.27	1.60	2.24	0.47	0.29
G53	1.04	0.30	0.29	2.33	1.62	2.50	0.52	0.40
G54	1.24	0.35	0.31	1.74	1.47	2.09	0.58	0.37
G55	0.96	0.24	0.18	2.09	1.06	1.93	0.34	0.16
G56	1.15	0.34	0.24	2.29	1.48	3.02	0.47	0.39
G57	1.23	0.26	0.30	2.34	1.60	1.91	0.35	0.20
G58	1.36	0.31	0.31	2.31	1.54	1.84	0.48	0.35
G59	1.37	0.25	0.34	2.06	1.50	1.90	0.38	0.30
G60	1.38	0.30	0.33	1.91	1.18	2.21	0.41	0.19
G61	1.21	0.27	0.30	1.98	1.22	1.06	0.37	0.21
G62	1.55	0.37	0.37	1.84	1.47	2.11	0.48	0.32
G63	1.30	0.37	0.34	2.26	1.41	2.52	0.51	0.36
G64	1.26	0.36	0.32	2.36	1.76	1.42	0.40	0.22
G65	1.37	0.26	0.36	2.51	1.77	1.96	0.37	0.29
G66	1.46	0.30	0.40	2.34	1.88	1.78	0.52	0.36
G67	1.33	0.27	0.39	2.43	1.75	1.85	0.47	0.33
G68	1.38	0.29	0.31	2.09	1.44	1.04	0.32	0.19
G69	1.36	0.26	0.28	2.38	1.60	1.60	0.43	0.36
G70	1.34	0.29	0.36	2.35	1.81	1.67	0.42	0.36
G71	1.53	0.28	0.29	2.53	1.64	1.87	0.42	0.39
G72	1.31	0.45	0.35	1.79	1.91	2.34	0.70	0.37
G7.1	1.29	0.31	0.38	2.54	1.11	2.14	0.42	0.34
G7.2	1.56	0.34	0.32	2.30	1.62	1.44	0.59	0.35
G7.3	1.46	0.33	0.35	2.54	1.22	2.12	0.52	0.38
G7.4	1.64	0.32	0.22	2.28	1.47	1.58	0.54	0.32
G7.5	1.72	0.34	0.29	2.21	1.28	1.80	0.48	0.36
G7.6	1.38	0.28	0.31	2.78	1.21	1.81	0.47	0.35
G7.7	1.40	0.31	0.31	2.54	1.37	2.21	0.49	0.37
G7.8	1.39	0.27	0.30	2.29	1.31	1.67	0.49	0.35
G7.9	1.32	0.25	0.30	2.61	1.52	1.81	0.43	0.29
G7.10	1.26	0.26	0.27	2.35	1.29	1.89	0.49	0.36
G7.11	1.39	0.28	0.33	2.35	1.19	2.01	0.31	0.16
G7.12	1.42	0.33	0.30	2.04	1.32	1.84	0.51	0.17
G7.13	1.31	0.30	0.31	2.23	1.41	1.65	0.40	0.28
G7.14	1.70	0.33	0.29	2.39	1.07	1.86	0.31	0.23
G7.15	1.52	0.27	0.24	1.96	1.34	1.91	0.28	0.20
G10.1	1.35	0.28	0.31	2.31	1.63	1.69	0.42	0.16
G10.2	1.61	0.29	0.36	2.06	1.51	1.73	0.45	0.36

G10.3	1.61	0.30	0.34	2.28	1.51	1.37	0.30	0.23
G10.4	1.50	0.29	0.32	2.79	1.73	1.91	0.40	0.35
G10.5	1.61	0.29	0.30	2.62	1.24	1.58	0.31	0.20
G10.6	1.59	0.27	0.31	2.86	1.51	1.80	0.27	0.19
G10.7	1.21	0.25	0.30	2.37	1.61	1.92	0.42	0.25
G10.8	1.11	0.31	0.26	1.94	1.33	1.55	0.30	0.16
G10.9	1.58	0.31	0.34	2.45	1.19	1.66	0.30	0.20
G10.10	1.62	0.32	0.33	2.38	1.53	2.19	0.38	0.32
G10.11	1.61	0.33	0.36	2.71	1.41	1.75	0.35	0.19
G10.12	1.55	0.30	0.28	2.82	1.13	1.60	0.28	0.14
G10.13	1.57	0.29	0.22	2.61	1.23	1.95	0.50	0.35
G10.14	1.79	0.34	0.37	2.38	1.61	2.13	0.46	0.37
G10.15	1.57	0.29	0.34	2.26	1.58	2.00	0.43	0.35
G21.1	1.39	0.39	0.29	1.55	1.43	1.17	0.59	0.29
G21.2	1.27	0.41	0.35	1.61	1.65	1.23	0.50	0.41
G21.3	1.27	0.37	0.30	1.49	1.47	1.59	0.57	0.34
G21.4	1.36	0.35	0.28	1.95	1.46	1.55	0.54	0.33
G21.5	1.38	0.38	0.35	2.13	1.64	2.07	0.63	0.37
G21.6	1.29	0.40	0.30	2.07	1.05	1.02	0.44	0.14
G21.7	1.33	0.39	0.20	1.87	1.52	1.70	0.58	0.39
G21.8	1.38	0.41	0.31	1.94	1.05	1.41	0.36	0.22
G21.9	1.39	0.40	0.33	1.94	1.64	1.32	0.58	0.36
G21.10	1.39	0.42	0.31	1.66	1.51	1.19	0.55	0.25
G21.11	1.19	0.40	0.32	1.74	1.32	1.28	0.48	0.24
G21.12	1.63	0.43	0.34	1.62	1.35	1.35	0.63	0.32
G21.13	1.23	0.40	0.34	1.40	1.47	1.41	0.66	0.39
G21.14	1.16	0.40	0.31	1.64	1.37	1.22	0.60	0.35
G21.15	1.22	0.43	0.32	1.67	1.32	1.16	0.61	0.35
G33.1	1.57	0.28	0.29	2.41	1.53	2.08	0.46	0.35
G33.2	1.56	0.30	0.33	2.50	1.36	2.27	0.39	0.31
G33.3	1.56	0.32	0.34	2.04	1.38	2.14	0.53	0.37
G33.4	1.47	0.28	0.33	2.70	1.49	1.71	0.37	0.26
G33.5	1.54	0.31	0.32	2.42	1.71	1.53	0.44	0.28
G33.6	1.49	0.28	0.33	2.47	0.97	1.16	0.25	0.19
G33.7	1.80	0.33	0.33	2.33	1.06	1.02	0.28	0.18
G33.8	1.58	0.33	0.32	2.75	1.56	2.13	0.46	0.33
G33.9	1.62	0.33	0.34	2.18	1.40	1.21	0.35	0.15
G33.10	1.68	0.36	0.36	2.40	1.59	1.27	0.35	0.15
G33.11	1.48	0.30	0.33	1.98	1.90	1.75	0.45	0.34
G33.12	1.48	0.32	0.31	2.07	1.34	1.69	0.30	0.22
G33.13	1.37	0.32	0.29	1.39	1.52	1.54	0.31	0.18
G33.14	1.54	0.30	0.32	1.92	1.60	1.86	0.40	0.19
G33.15	1.12	0.32	0.29	1.84	1.86	2.07	0.56	0.38
G46.1	1.14	0.29	0.23	2.38	1.24	2.19	0.35	0.49
G46.2	1.27	0.35	0.23	1.88	1.23	2.15	0.48	0.39
G46.3	1.09	0.32	0.28	2.29	1.04	1.70	0.33	0.19
G46.4	1.34	0.34	0.29	2.30	1.42	1.86	0.42	0.16

G46.5	1.27	0.32	0.29	3.00	1.52	1.44	0.56	0.20
G46.6	1.29	0.35	0.31	2.49	1.31	2.03	0.57	0.39
G46.7	1.18	0.33	0.30	2.49	1.14	1.69	0.37	0.16
G46.8	1.17	0.33	0.28	1.79	1.39	1.93	0.48	0.40
G46.9	1.25	0.32	0.24	2.55	1.33	2.37	0.43	0.15
G46.10	1.04	0.32	0.27	1.87	1.33	2.18	0.46	0.32
G46.11	1.10	0.30	0.27	1.95	1.88	1.87	0.42	0.36
G46.12	1.15	0.34	0.27	2.14	1.13	1.89	0.49	0.39
G46.13	1.06	0.29	0.28	2.66	1.50	2.49	0.48	0.40
G46.14	1.23	0.32	0.22	2.51	1.31	2.21	0.54	0.40
G46.15	1.21	0.34	0.31	2.45	1.37	1.83	0.52	0.39
G60.1	1.41	0.32	0.33	1.55	1.14	0.97	0.31	0.23
G60.2	1.43	0.28	0.28	2.08	1.80	1.60	0.47	0.28
G60.3	1.46	0.31	0.31	1.47	1.70	1.60	0.48	0.32
G60.4	1.57	0.31	0.35	2.19	1.69	1.35	0.41	0.14
G60.5	1.36	0.30	0.35	2.09	1.63	1.20	0.41	0.17
G60.6	1.45	0.26	0.33	2.53	1.56	1.61	0.38	0.30
G60.7	1.32	0.27	0.35	2.42	1.83	1.45	0.44	0.32
G60.8	1.34	0.25	0.32	2.17	1.86	1.28	0.51	0.35
G60.9	1.41	0.25	0.37	2.25	1.81	1.33	0.49	0.34
G60.10	1.32	0.23	0.28	2.55	1.48	1.43	0.34	0.31
G60.11	1.36	0.26	0.32	2.36	1.78	1.97	0.49	0.37
G60.12	1.32	0.28	0.35	1.86	1.75	1.54	0.42	0.32
G60.13	1.23	0.27	0.34	1.97	1.34	1.43	0.24	0.14
G60.14	1.54	0.28	0.36	2.54	1.09	1.30	0.27	0.14
G60.15	1.33	0.26	0.34	2.05	1.59	1.50	0.39	0.24

APPENDIX D Soil profile description

ARC • LNR

SOIL PROFILE DESCRIPTION

NATIONAL SOIL PROFILE NO : 14050
Map/photo : 2527DB Brits (4)
Latitude + Longitude: 25° 33' 9" / 27° 49' 49"
Land Type No :
Climate Zone :
Altitude : 1133 m
Terrain Unit: Footslope
Slope: 1 %
Slope Shape : Straight
Aspect : North
Microrelief : None
Parent Material Solum : Origin single, solid rock
Underlying Material : Basic intrusive rocks

Soil form and family : Shortlands pyramid
Surface rockiness :
Surface stoniness : None
Occurence of flooding : None
Wind erosion : None
Water Erosion : None
Vegetation / Land use : Agronomic cash crops
Water table : None
Described by : P. Steenekamp
Date Described : 4/2001
Weathering of underlying material: Advanced physical, strong chemical
Alteration of underlying material : Normal weathering

Horizon	Depth (mm)	Description	Diagnostic horizon
A1	0 - 250	Moist state; horizon disturbed; moist colour: dark reddish brown 2.5YR2.5/4; texture: clay; structure: moderate coarse subangular blocky; consistence: very hard, firm, sticky, plastic; many fine pores, medium cracks; common clay cutans; water absorption: 2 second(s); common roots; gradual smooth transition.	Orthic
B2	250 - 550	Moist state; horizon disturbed; moist colour: dark reddish brown 2.5YR2.5/4; texture: clay; structure: moderate coarse subangular blocky; consistence: very hard, firm, sticky, plastic; many fine pores, fine cracks; non-hardened free lime, slight effervescence; common clay cutans; water absorption: 1 second(s); common roots; clear smooth transition.	Red structured
B3	550 - 1100	Moist state; horizon undisturbed; moist colour: dark reddish brown 2.5YR3/4; texture: clay loam; common fine faint white lime mottles; common fine faint yellow, brown and red reduced iron oxide mottles; structure: moderate medium subangular blocky; consistence: very hard, firm, slightly sticky, slightly plastic; common fine bleached pores; non-hardened free lime, strong effervescence; common clay cutans; few fine <2-6mm lime concretions; water absorption: 1 second(s); few roots; clear smooth transition.	Saprolite
C	1100 - 1101+	Moist state; moist colour: strong brown 7.5YR5/6; structure: apedal massive; consistence: slightly hard, slightly firm, non-sticky, non-plastic; few fine pores; non-hardened free lime, slight effervescence; water absorption: 1 second(s); few roots.	Saprolite

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SOIL PROFILE DESCRIPTION

NATIONAL SOIL PROFILE NO : 14049

Map/photo : 2527DB Brits (4)

Latitude + Longitude: 25° 33' 12" / 27° 49' 50"

Land Type No :

Climate Zone :

Altitude : 1136 m

Terrain Unit: Footslope

Slope: 1 %

Slope Shape : Straight

Aspect : North

Microrelief : None

Parent Material Solum : Origin single, solid rock

Underlying Material : Basic intrusive rocks

Soil form and family : Hutton stella

Surface rockiness : None

Surface stoniness : None

Occurence of flooding : None

Wind erosion : None

Water Erosion : None

Vegetation / Land use : Agronomic cash crops

Water table : None

Described by : P. Steenekamp

Date Described : 4/2001

Weathering of underlying material: Strong physical, strong chemical

Alteration of underlying material : Normal weathering

Horizon	Depth (mm)	Description	Diagnostic horizon
A1	0 - 300	Moist state; horizon disturbed; moist colour: dark reddish brown 2.5YR2.5/4; texture: clay; structure: weak coarse subangular blocky; consistence: very hard, firm, sticky, plastic; fine cracks; water absorption: 1 second(s); common roots; gradual transition.	Orthic
B1	300 - 1000	Moist state; horizon undisturbed; moist colour: dark reddish brown 2.5YR2.5/4; texture: clay; structure: apedal massive; consistence: very hard, firm, sticky, plastic; fine cracks; few clay cutans; water absorption: 1 second(s); common roots; gradual transition.	Red apedal
C1	1000 - 1200+	Moist state; horizon undisturbed; structure: apedal massive; consistence: hard, firm, slightly sticky, non-plastic; non-hardened free lime, slight effervescence; water absorption: 1 second(s); few roots.	Saprolite

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APPENDIX E Photo gallery